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Report No. IITRI E6047-7

Final Report

STUDY CONCERNING NONLINEAR MIXING OF RADIO FREQUENCY SIGNALS IN STEEL STRUCTURES

NASA - J.F. Kennedy Space Center

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Contract No. NAS 10-2154

IITRI Project E6047

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ABSTRACT

Interference noted during the checkout of several Saturn vehicles was determined to be generated within the launch service structure. The interference was discrete frequency intermodulation generated by nonlinearities within the structure which were excited by radiating vehicular systems. The purpose of the present program was to determine what nonlinear phenomena were responsible for this interference and to develop methods for locating and eliminating the sources.

Preliminary investigations on the program revealed that two nonlinear phenomena, which exist in most environments, are capable of generating interference at UHF frequencies. The most significant of these two mechanisms is the nonlinear impedance which can be formed at the contact point between two metal surfaces. The other mechanism is the nonlinear magnetization characteristic of ordinary steel. Quite high fundamental current densities are necessary before significant interference levels can be generated in steel; however, care should be exercised in the use of this material in transmitting output circuits and antennas.

A technique has been developed which permits contact nonlinearities arbitrarily distributed within an environment, such as a service structure, to be successfully located. The technique relies on a directional antenna system to locate the approximate area from which nonlinearly generated signals

emanate. The nonlinearities within the isolated area are then pinpointed by use of a small loop probe or an audio probe.

The composite location technique was used to investigate typical areas of a launch service structure. A significant number of nonlinearities capable of creating interference to a vehicle system were pinpointed. Several categories of structural components and construction techniques were found to consistently produce potentially severe interference conditions.

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STUDY CONCERNING NONLINEAR MIXING OF RADIO FREQUENCY SIGNALS IN STEEL STRUCTURES

I. INTRODUCTION

On November 20, 1963[1], during the electromagnetic compatibility tests being performed by the Electromagnetic Section (K-ES02) on SA-5 at Launch Pad 37, interference was noted on the S-IV Command Destruct Receiver. An increase in the AGC level of the receiver was noted when all RF systems were turned on.

Subsequent testing resulted in the determination that radiations from the telemetry systems were mixing with the UDOP transponder output signal and creating a discrete frequency interference signal at the Command Destruct Receiver frequency. Further investigations by the Electromagnetic Section (K-ES02) evidenced that the discrete frequency interference being observed was not "system generated". That is, the interference was not being conducted into the system via power or control leads, nor was the interference being created in the transmitter output or receiver input stages. Additional tests indicated that the discrete frequency interference was being created in the environment external to the vehicle; namely, the service

[1]"Report on Electromagnetic Interference Problems of SA-5" Electromagnetics Section Engineering Support Division Assistant Director for Instrumentation IN-K-ES2-64-1, February 14, 1964, J.F. Kennedy Space Center.

structure and umbilical tower. However, attempts to determine the nonlinear points were unsuccessful.

The interference problems described here are not restricted to SA-5 or pad 37; nor are they amenable to solution by simple frequency assignment plans. The problems are the result of structures being immersed in intense RF fields, and they are compounded as the number of radiated signals and power levels increases.

Theoretical and experimental investigations were conducted into the nature of such nonlinear mixing of radio frequency signals in steel structures at frequencies above the HF band. The work was directed toward the development of techniques and devices which would allow field personnel to locate nonlinearities capable of creating intermodulation interference in launch service structures. Investigation of typical service structures, utilizing the developed techniques and devices, was also undertaken to determine categorically what presently employed construction practices are prone to the generation of such nonlinear interference.

II. LABORATORY STUDIES OF ENVIRONMENTAL NONLINEAR PHENOMENA

A. Comparative Investigation of Two Known Phenomena

Investigations by IITRI in the field of environmental nonlinearly-generated discrete frequency interference have shown that at least two different mechanisms can give rise to such interference. These two phenomena are the nonlinear hysteresis effects in ferromagnetic materials and the nonlinear impedance which results from oxided, metallic mating surfaces.

At the outset of this program, only limited information was available on the effects of these two phenomena at frequencies above the HF band. Since the problems encountered at Cape Kennedy involved frequencies in the space telemetry band (i.e., 230 to 360 Mc) and also frequencies of the order of 450 Mc and 900 Mc, initial investigations on the program were concerned with establishing the relative significance of these phenomena as environmental interference contributors within the frequency range of interest.

1. Verification of Steel Effects at VHF Frequencies

Past research at IITRI has shown that the nonlinear properties of ferromagnetic materials such as steel can create interference at HF frequencies if the current densities flowing in the steel components are sufficiently high. There is a dearth of information on this phenomenon at RF frequencies in the literature other than a few comments on the possibility that hysteresis ceases to exist in most magnetic materials somewhere between 100 Kc and 10 Mc.[2] Therefore, a brief series of tests was developed to ascertain whether the nonlinear ferromagnetic effect was a potential interference mechanism at VHF frequencies.

a) Transmission Line Test

In order to determine if sufficiently high current density in a steel wire would generate nonlinear signals at VHF frequencies, two 50-ohm transmission lines were designed: one of non-magnetic tungsten wire having a 2.2 mils diameter and a resistance of 15 ohms/meter, the other of magnetic steel wire having a 3.0 mils diameter and a resistance of 22 ohms/meter. The two types of wires were reasonably similar in characteristics except for the magnetic property of the steel. The test was carried out at 200 Mc and at 330 Mc, and in each case the third harmonic generated was measured as a function of the fundamental power level. The test setup appears in Figure 1 and the data are recorded in Table 1. The results show that steel is still nonlinear at those frequencies.

b) Monopole Antenna Test

The experiment on the transmission lines showed that steel retains its nonlinear properties even at VHF frequencies. A test was needed to determine if a nonlinear signal generated in steel could be re-radiated at a sufficiently high level to

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[2] "The Permeability of Ferromagnetic Materials at Frequencies Between 10^5 and 10^{10} c/s", J.T. Allanson, J. Inst. Elect. Engrs. G.B. December, 1945, 92, III, pp 247-255.

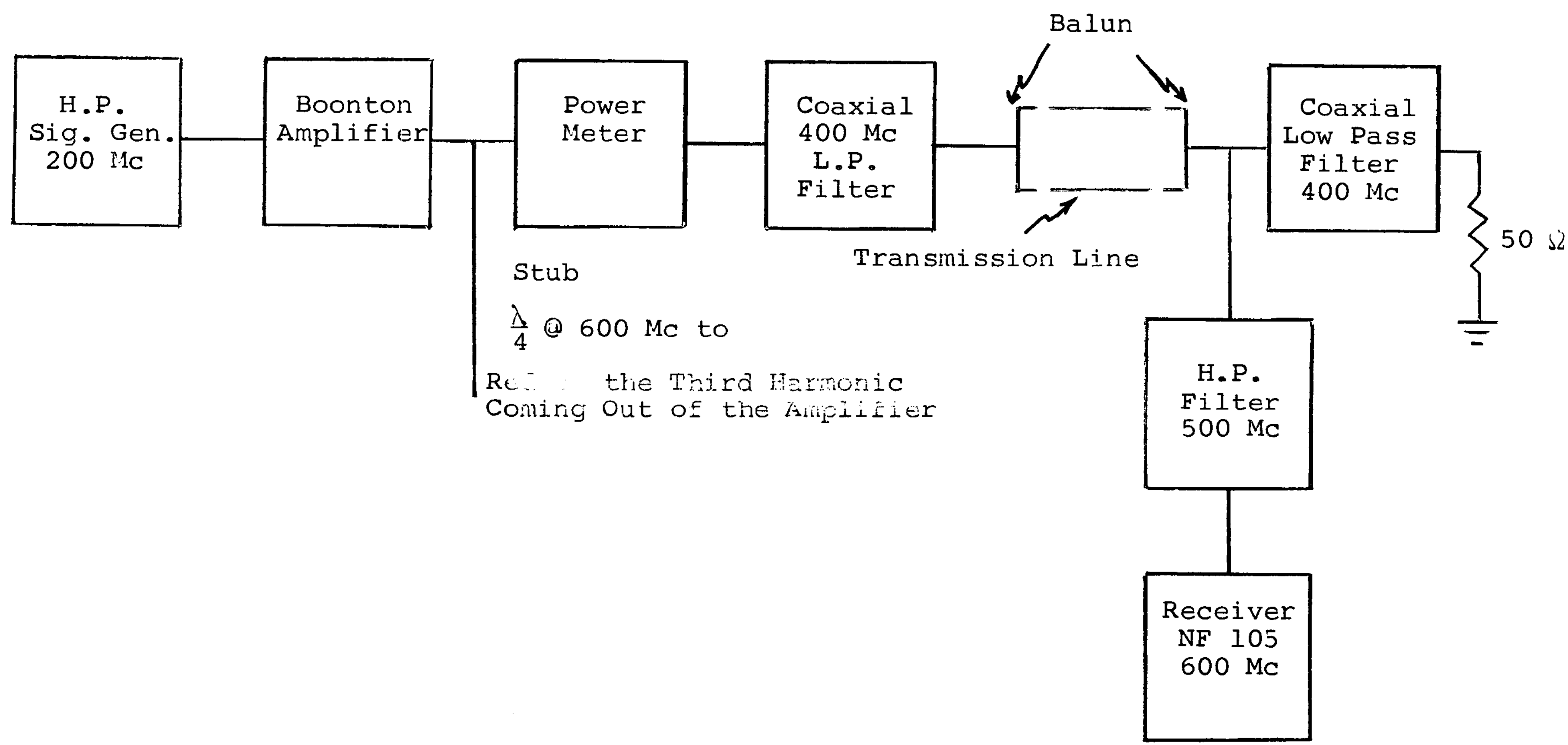


FIGURE 1 VHF TEST OF STEEL TRANSMISSION LINE

Fund. Power Watts	200 Mc		330 Mc	
	Third Harmonic Level		Third Harmonic Level	
	Tungsten Wire	Steel Wire	Tungsten Wire	Steel Wire
0.2	---	---	0	0
0.6	---	---	0	5 db/noise
1.0	---	22 db/noise	0	8.2 db/noise
2.0	1 db/noise	27 db/noise	0	11.5 db/noise
3.0	2 db/noise	29 db/noise	0	14 db/noise
4.0	5.5 db/noise	31 db/noise	$\frac{1}{2}$ db/noise	10 db/noise
5.0	9 db/noise	32.5 db/noise	$\frac{1}{2}$ db/noise	---

TABLE 1

be picked up by a receiving antenna. For this purpose, two monopole antennas were mounted on a small aluminum ground plane (19" x 35"). One antenna was made of 36 mils copper wire and cut to a quarter wavelength at 600 Mc (i.e., the third harmonic of 200 Mc) and used as the receiving antenna. As a transmitting antenna, three different types of wire were used:

a) magnetic steel wire (3 mils),
b) copper wire (36 mils),
c) tungsten wire (2.3 mils).

The transmitting antennas were cut to a quarter-wavelength at 200 Mc, and the test was carried out using each transmitting antenna, in turn, on the small ground plane. Figure 2 shows the test setup and Table 2 contains the data obtained from the experiment.

These results show that the harmonic level was higher with the steel antenna than with either the tungsten wire antenna or the copper antenna, yet some nonlinear signals were measured with these two supposedly linear antennas. It is believed that the signals received on the "linear" antennas were due to the fact that the environment was illuminated by strong fundamental fields which generated nonlinear signals in the environmental junctions situated in the vicinity.

From the data in Table 2, it can be noted that the third harmonic signals received were erratic for transmissions from the copper and tungsten antennas, while the received signal was steady when the steel antenna was used. The above observation supports the hypothesis that the signals received on the copper

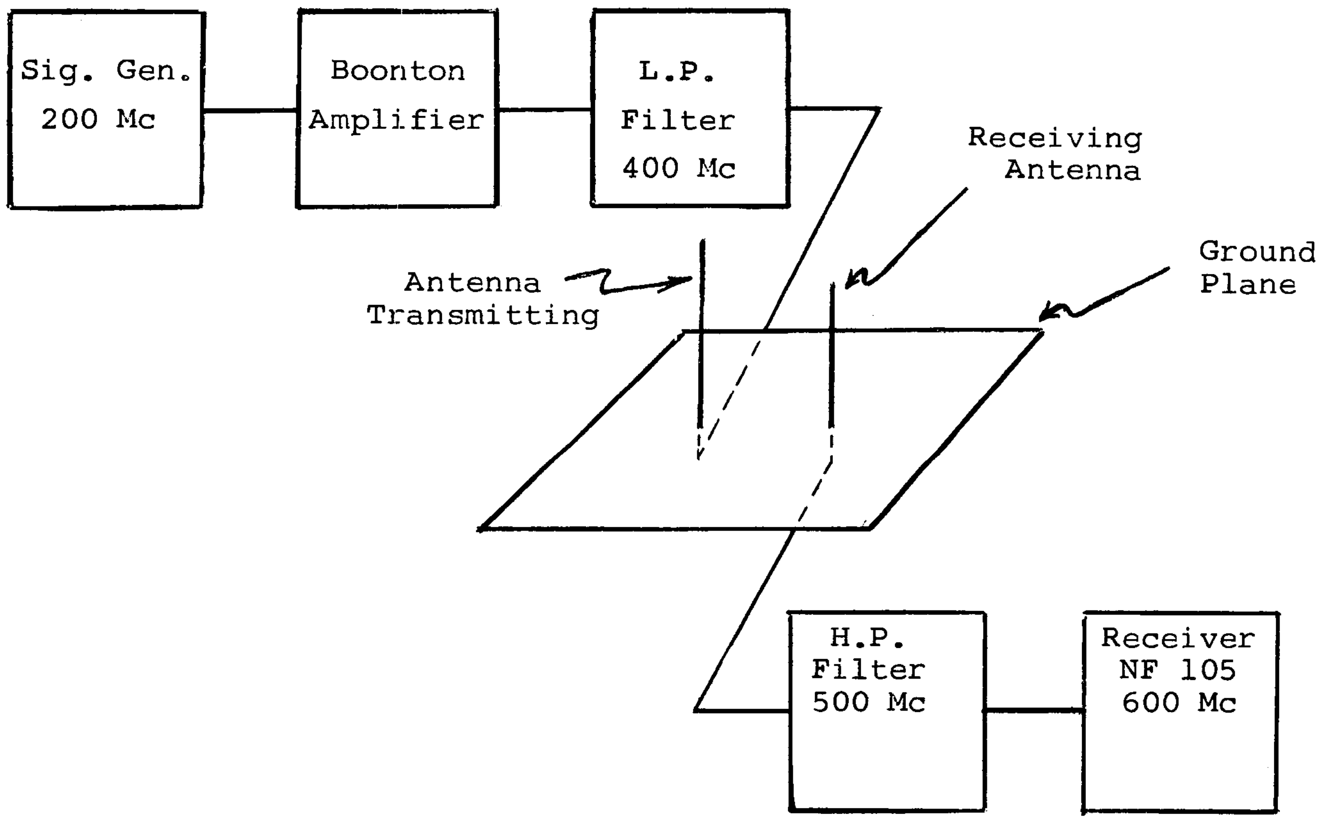


FIGURE 2 VHF TEST OF STEEL ANTENNA

Fundamental Power Level in Watts @ 200 Mc	Third Harmonic (600 Mc) Level Measured on Receiving Antenna When Three Different Transmitting Antennas Were Used		
	Antenna 1 Magnetic Steel Wire (3 mils)	Antenna 2 Copper Wire (36 mils)	Antenna 3 Tungsten Wire 2.3 mils
.5	20 db/noise	4 10 db/noise	6 – 9 db/noise
1	24 db/noise	14 20 db/noise	11 – 13 db/noise
2	28.5 db/noise	20 db/noise	15 – 17 db/noise
3	32 db/noise	23 db/noise	20 db/noise
4	33.5 db/noise	23 db/noise	22 db/noise
5	35 db/noise	24 db/noise	20 db/noise
	Reading Steady	Reading Bouncy	Reading Bouncy

TABLE 2 ANTENNA TEST DATA

and tungsten antennas were generated by junctions in the environment.

Experience has shown that environmental junction-type nonlinearities are often electrically unstable, thus giving rise to erratic signals. However, the nonlinear mechanism in steel produces distortion components which are constant in magnitude. Thus, in the test described, the third harmonic signal received when the steel transmitting antenna was used was constant for a given radiated power level. The aberrant signal contribution from the environmental junctions was undoubtedly being masked by the stronger steel contribution

The results of the investigation indicate that steel is sufficiently nonlinear at VHF frequencies to create intermodulation products if the fundamental current densities within the steel are high. However, in the tests which were conducted, the steel was used as the primary current flow path rather than being arbitrarily located in the environment. Thus, the experimental results tend to suggest a policy of not using steel antennas or transmission path components without a detailed test to determine whether, under normal operating conditions, the current densities are sufficiently low to preclude the generation of interference within these components. More extensive research is necessary to determine what, if any, contribution to the environmental generated interference can be attributed to steel.

However, it is believed that, with the exception of transmitter system components and antennas, the nonlinear effects of steel in the environment on the generation of interference are secondary in importance to that presented by nonlinear contacts. The major research emphasis on this program was, therefore, concentrated on the problem of characterizing and locating such nonlinear contacts within the environment.

2. Behavior of Junctions at VHF Frequencies

The previous experiment on steel evidenced what appeared to be environmental junctions generating interference at VHF frequencies. This phenomenon could be deduced from the erratic nature of the third harmonic signal when the copper and the tungsten antennas were used.

A more controlled experiment was performed on a 14-foot brass ship model, which was available from another IITRI project. The model contained numerous natural junctions, having been outside for almost a year. The test was conducted in the following way. A fundamental frequency of 200 Mc at a power level of approximately two watts was radiated from a set of fan antennas on the model. The third harmonic was then received on a whip antenna, which was also on the ship model. The signal received had the erratic characteristic of HF band interference signals generated by naturally occurring junctions. Other combinations of transmitting and receiving antennas were tried with the same results.

The most practical method of locating contributing junctions on the ship model was by moving various structures, applying pressures at various points until the received signal increased or decreased.

A considerable amount of bonding was done, and the model was finally cleaned enough so that very little third harmonic could be detected. The task of bonding was relatively easy because the model was fairly small, and the possible junctions in the vicinity of the transmitting and receiving antennas were relatively obvious. The most bonding was done around the aft main mast, where a loose radar antenna was soldered and the cabling running down the mast was bonded to the mast. The after gun directors were removed and a few places were bonded near the aftermast. Much of the bonding was unnecessary, but it was found that only by grounding most of the possible junctions could the real contributors be cured. It was not always the most obvious junctions that were the worst offenders.

The test showed that junction-type nonlinearities within the immediate environment of the antenna system could generate significant interference. Additional tests within the laboratory showed that radiated VHF signals could excite numerous nonlinearities within the laboratory, such as tools and equipment on benches, metallic ceiling panels, metallic bench frames, and other metallic items.

B. <u>Test of Service Structure Paint</u>

During the investigation of potential environmental nonlinear sources, concern was expressed as to the possible nonlinearity of the paint which is used throughout the service structure.

In an attempt to resolve the questions which had been raised, a short series of tests was conducted on this point.

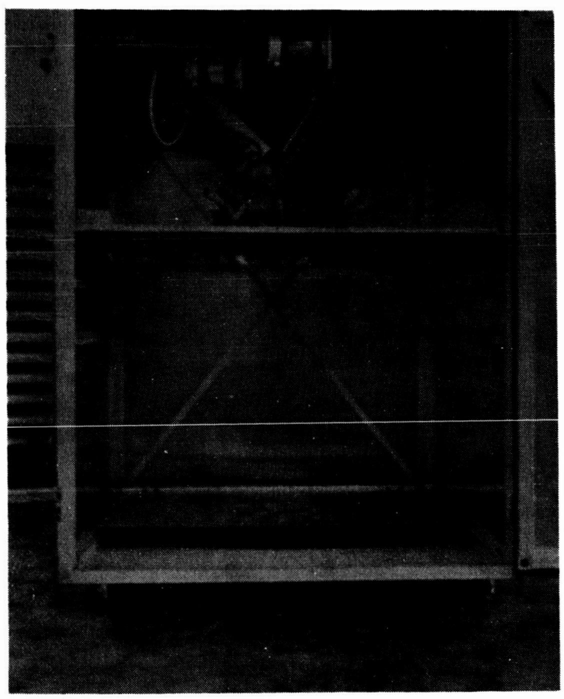


FIGURE 3 LABORATORY NONLINEARITY TEST FACILITY

For the paint test a permanent nonlinear test facility which was available in the laboratory was utilized. This facility was built for the purpose of testing various structural components and materials. Figure 3 is a photograph of the facility which consists of a chamber in which three resonant circuits are mounted. Two of the circuits can be driven by two HF band transmitters, while the third resonant circuit is tuned to a harmonic or intermodulation frequency. The output of this third circuit is fed to a receiver system. Samples to be tested were placed on a wooden shelf such that the samples were within the strong induction fields of the coils.

To test the paint linearity, a total of fifteen samples were made from three different materials. The sample materials were brass, aluminum, and steel. The samples were of uniform gauge (0.02 inches) and were cut to a standard 3 inch by 6 inch size. The test utilized a single transmitter at 2.025 Mc which delivered 100 watts to one of the tuned circuits. The receiver system was tuned to the third harmonic at 6.075 Mc. The following sequence of measurements were made on the group of samples:

1. Reference third harmonic levels were obtained for single unpainted samples of each type metal.
2. Reference third harmonic levels were obtained for all combinations of two unpainted samples, i.e., steel and aluminum, steel and brass, aluminum and brass, etc. For this test the two samples were

joined with a one-inch overlap in the narrow dimension. The two samples were held together firmly with tape.

3. One sample of each type metal with primer applied to one side was tested.

4. One sample of each type metal with both primer and finish coat applied to one side was tested.

5. All combinations of two samples were tested with one side of each sample painted with both primer and finish coat. The samples were overlapped as in test number 2; however, for this test the painted sides of the samples were joined together while the finish coat of paint was still wet. The paint, when dried, formed a mechanical bond between the two samples; however, there was not electrical continuity from one sample through the paint junction to the other sample.

The data obtained by the above series of tests are presented in Table 3. It can be seen that the harmonic signals produced by the samples can be directly attributed to the steel effect. Thus, the test indicates that the service structure paint should not contribute to the interference generated within these structures.

The above test does not constitute an exhaustive study of the paint, since only a single frequency in the HF band was used. However, the effects of steel wire clearly evident in this test and the nonlinear contribution of steel h[illegible] been relegated to a secondary position with respect to the interference contribution of contacts; therefore, any contribution from the paint is surely a second or third order effect compared to the contact problem.

Test No.	Sample	Position	Received Third Harmonic Level in db Signal/Noise
1.	Steel Alone		23
	Brass Alone		0
	Aluminum Alone		0
2.	Steel and Brass		24
	Steel and Aluminum		23
	Steel and Steel		27
	Brass and Aluminum		0
	Brass and Brass		0
	Aluminum and Aluminum		0
3.	Steel(Primer Coat)	Painted Side Exposed	23
		Unpainted Side Exposed	22
	Brass(Primer Coat)	Painted Side Exposed	0
		Unpainted Side Exposed	0
	Aluminum(Primer Coat)	Painted Side Exposed	0
		Unpainted Side Exposed	0
4.	Steel(Finish Coat)	Painted Side Exposed	22.5
		Unpainted Side Exposed	22.5
	Brass(Finish Coat)		0
	Aluminum(Finish Coat)		0
5.	Steel and Brass (Finish)	Steel Exposed	24
		Brass Exposed	24
	Steel and Aluminum(Finish)	Steel Exposed	24.5
		Aluminum Exposed	24.5
	Steel and Steel(Finish)		27
	Brass and Aluminum(Finish)		0
	Brass and Brass(Finish)		0
	Aluminum and Aluminum(Finish)		0

TABLE 3

PAINT TEST DATA

III. INVESTIGATION OF TECHNIQUES FOR LOCATING ENVIRONMENTAL NONLINEARITIES

Initial investigations of the program established the requirements and guidelines for the remaining phases of research. The interference contribution of nonlinear contacts within the environment was of such significance to warrant primary emphasis in the development of techniques and devices to pinpoint the location of these nonlinearities. The research efforts expended in the development of such techniques and devices are discussed in this section.

A. VHF Tests of Previously Developed Location Techniques

Due to the results of prior research into the phenomena of environmental nonlinear contacts, several devices and techniques for locating interference sources at frequencies below the VHF band were available at the outset of the present research effort. Preliminary efforts in determining a suitable methodology for locating VHF-UHF band interference contributors were directed toward evaluating the more useful lower frequency techniques at the frequency range of interest.

1. Audio Technique

This technique permits nonlinearities which are excited by the main radiated field to be located by an audio sensitive probe that responds to the modulation of the exciting RF field. The modulation is translated to the audio range by the nonlinearity of the excited junction. A description of the probe is given in Appendix A. The technique has been proven to be effective in the HF band. Experiments were performed at 200 Mc, 500 Mc, 1000 Mc, 2000 Mc,and 2500 Mc, and the method was found to be effective in every case.

Such a probe would be most useful if it were more sensitive than a simulated vehicle receiving system. In other words, the audio detector should be capable of detecting high impedance junctions that are beyond the detectable range of a good receiving system.

A test was conducted to assess the sensitivity of the audio probe relative to a quarter wave monopole used to receive a third harmonic generated in a diode. A two-watt signal at 200 Mc was radiated from a fan antenna on the ship model. The third harmonic was received on a 600 Mc quarter wave whip antenna located in the forward section of the ship. A diode at the base of a 200 Mc quarter wave monopole above a ground plane, completely remote from the ship, was used to generate the third harmonic. Figure 4 illustrates the experimental setup. As the diode was taken further and further away from the ship, the received third harmonic signal gradually faded out. When the signal was completely lost due to the large distance between the ship model, where the transmitting and receiving antennas were located, and the monopole containing the diode, the audio locator could still easily detect the audio tone across the diode. The diode was then taken twice as far from the ship model and could still be detected by the audio probe.

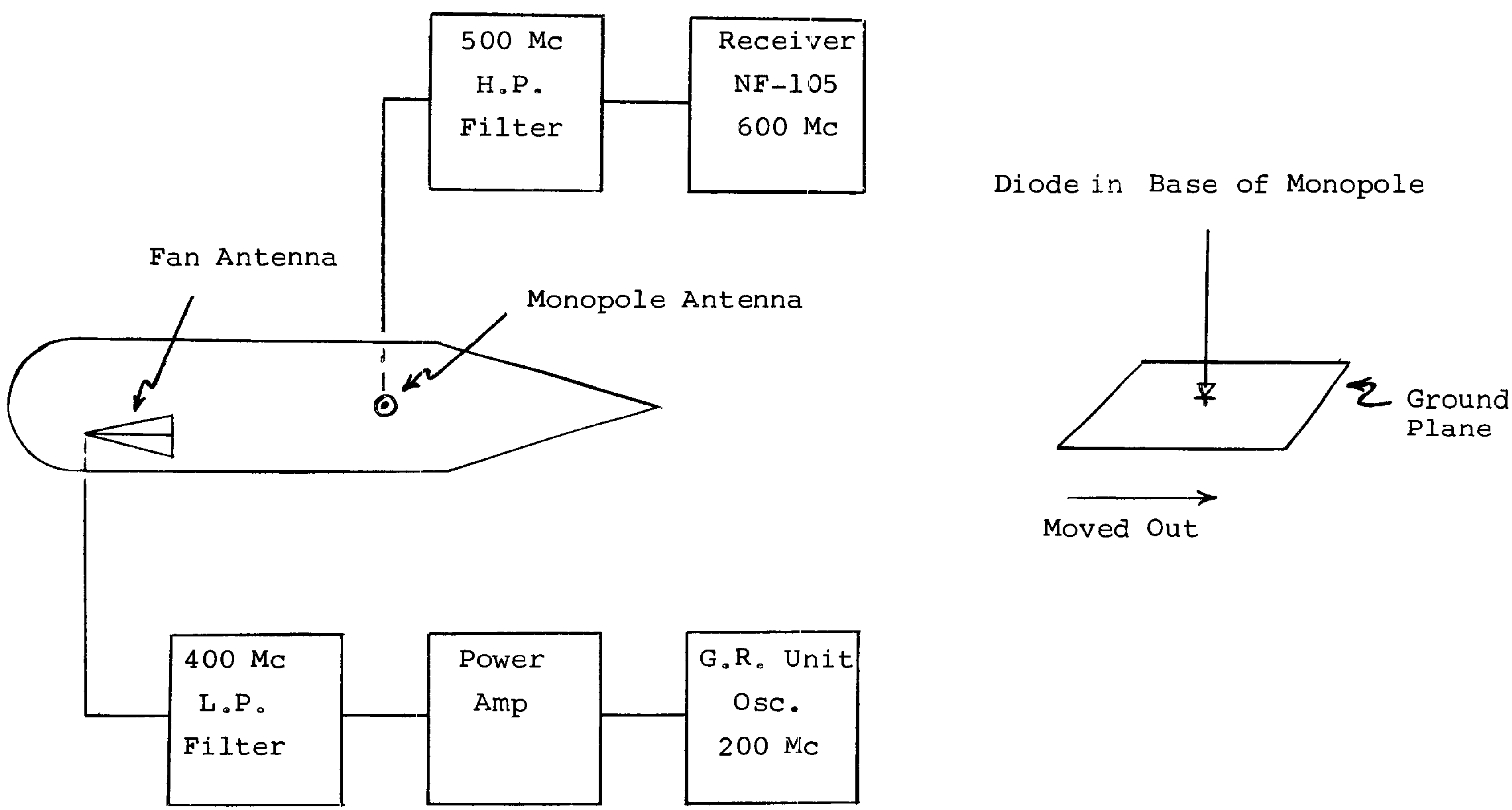


FIGURE 4 AUDIO LOCATOR TEST

Thus, the audio detector appears considerably more sensitive than the reference receiving system. A formal test on the sensitivity of the probe can be found at the end of Appendix A. It must be remembered, however, that this detection device is only useful in locating nonlinear contacts in relatively high impedance paths.

2. Signal Substitution Technique

This technique utilizes local signal substitution to determine whether a particular structure or nonlinearity is a contributor to the external environment-generated intermodulation received on a given receiving system. The test is run in the following way. Two signals are radiated from a pair of transmitting antennas. The intermodulation product frequency is sensed on a receiving antenna and the level A_T recorded. Then, a current probe is clamped around the suspected structure, and the level of the signal f_1 flowing in that structure is measured on a field intensity meter and recorded as E_1. The transmitter, T_{x_1}, is then turned off and the signal f_1 is induced back into the structure with a current probe and a signal generator until the field intensity meter reads the same level E_1 as before. (See diagram in Figure 5). Therefore, as far as that particular structure is concerned, the currents flowing in it are the same as when both signals were radiated. The intermodulation product level, A_p, received on the receiving antenna is an indication of the contribution of that particular structure to the total signal, A_T.

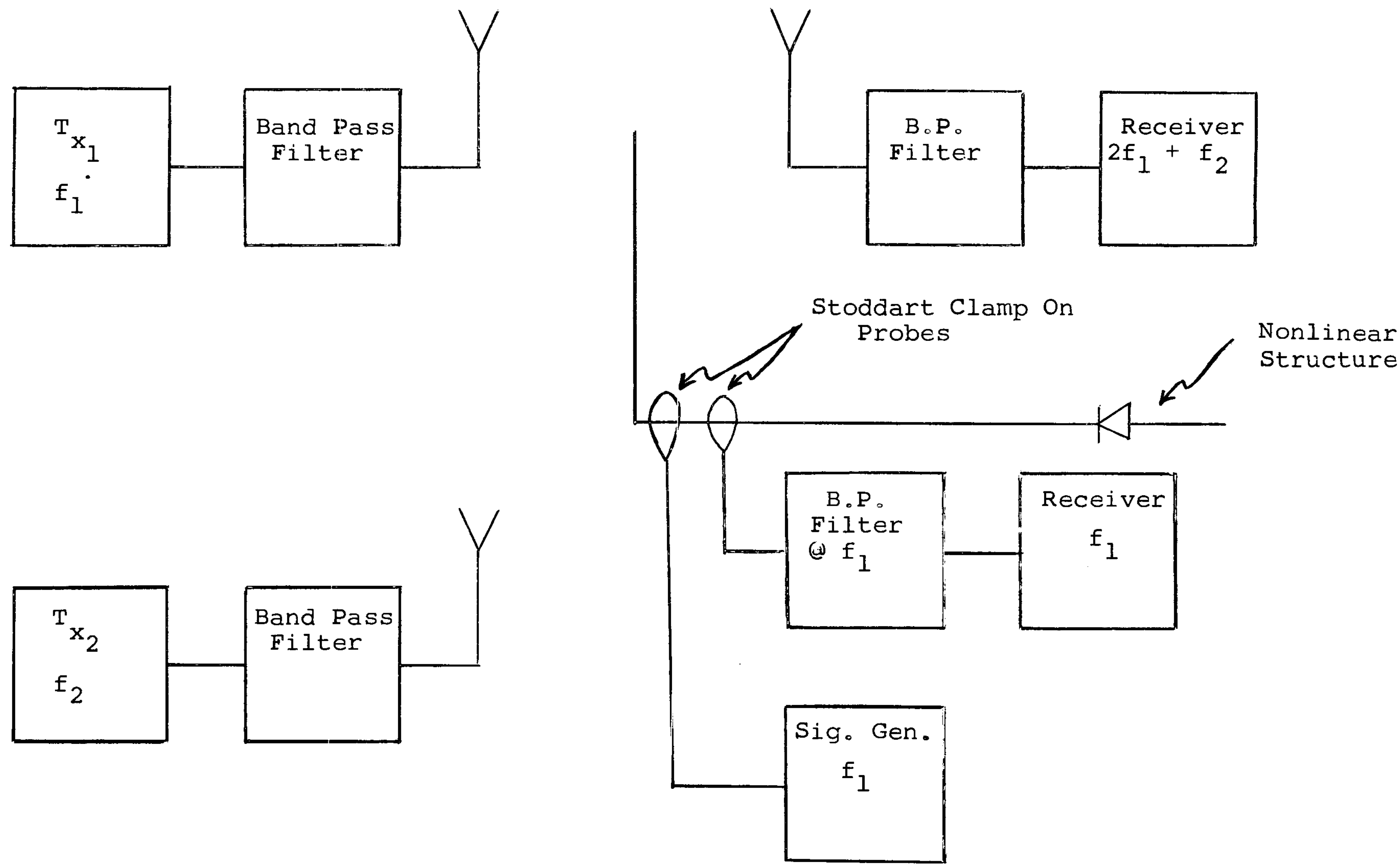


FIGURE 5 SIGNAL SUBSTITUTION TECHNIQUE

This technique, which has been used successfully in the HF band, was not utilized to a great extent on the present program. The technique is particularly useful in situations where a great number of nonlinearities which are difficult to fix are in a given area. With this situation, it may be desirable to determine which of the nonlinearities are actually contributing to the interference received on a given system, such that fixes need be applied to only the contributors.

3. <u>Loop Probe Technique</u>

Some situations exist where the audio probe technique will not work. For instance, if the junction is located in a loop, then the shorted path will prevent the audio signal from being detected across the junction. Such a situation is common, and means of detecting these nonlinearities are necessary. For that reason another technique using a small loop probe is employed. The probe used is an AT-426/U loop antenna, which is a three-inch loop similar to that furnished as standard equipment with many field intensity meters. The technique consists of inducing, with the loop probe, a fundamental signal at a point where a nonlinearity is suspected to be, and receiving on the same probe the third harmonic of the fundamental. Figure 6 shows a block diagram of the test setup.

An RF power amplifier is used in this technique because the signal fed to the probe has to be reasonably high due to the rather poor coupling efficiency from the probe to any particular

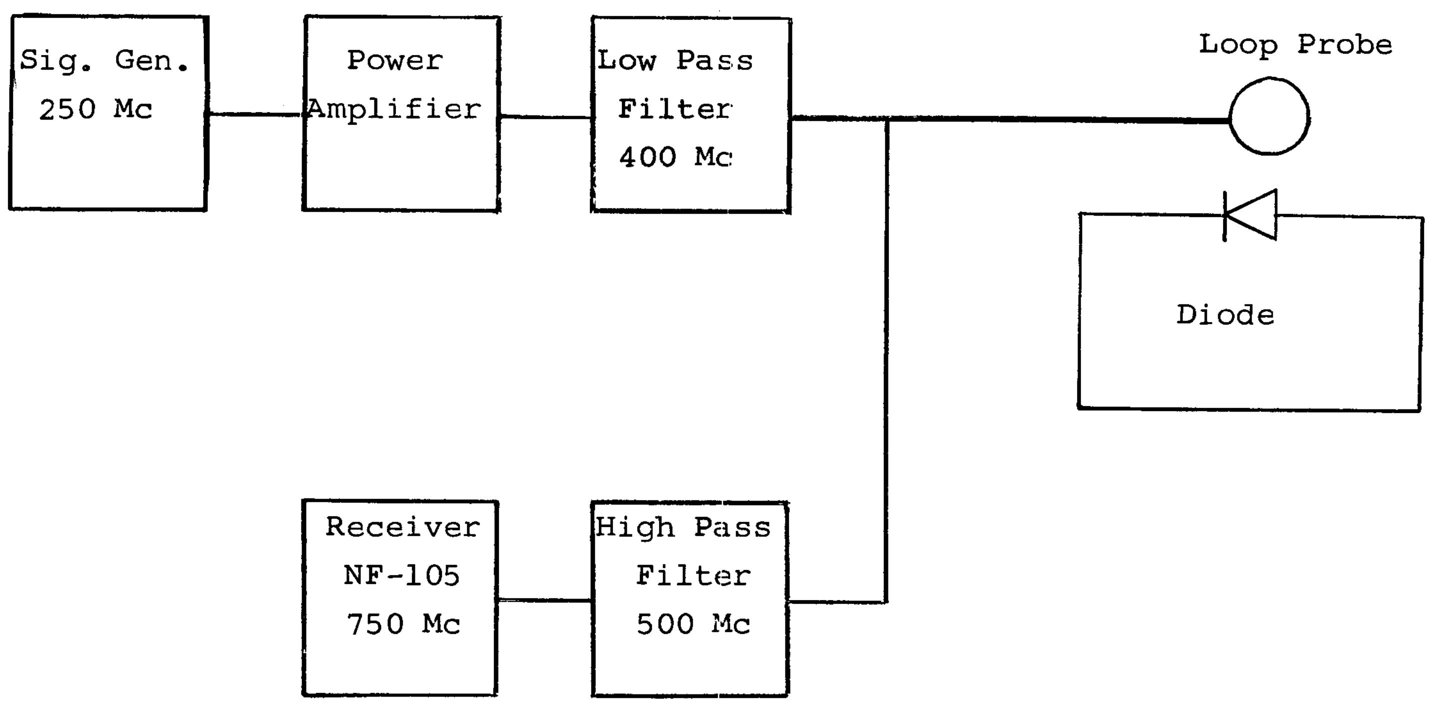


FIGURE 6 LOOP PROBE TECHNIQUE

structure. The loop probe technique is used in situations where the clamp-on current probe cannot be used for signal substitution due to the particular shape of the structure involved. In such a case, instead of receiving the third harmonic on the same loop probe, it is received on the normal receiving antenna. The draw-back of this method is that at times it is difficult to couple sufficient signal into the structure with the loop probe to drive the nonlinearity enough to influence the signal received on the antenna. But in a limited environment the technique is efficient, as was demonstrated in the experiment described in the following paragraph.

An investigation was made to determine the points of nonlinearity within a shielded enclosure. The enclosure tested was of the solid galvanized steel type. The tests indicated that the nonlinearities could be located by local signal injection with a small loop probe.

The presence of nonlinearities within the enclosure was determined by radiating a well-filtered 250 Mc signal from a cone antenna mounted within the enclosure and receiving the third harmonic of the radiated signal on the same antenna. The enclosure nonlinearities were found to be primarily in the floor joints. Figure 7 shows a typical floor joint in the enclosure. The presence of a nonlinearity at a particular joint could be determined by inducing a fundamental signal into the joint by means of the loop probe and receiving the third harmonic on either the loop probe or the cone antenna. The joint nonlinearity could not be detected by use on the audio voltage probe because all the nonlinearities had a shorted path furnished by the shielded enclosure.

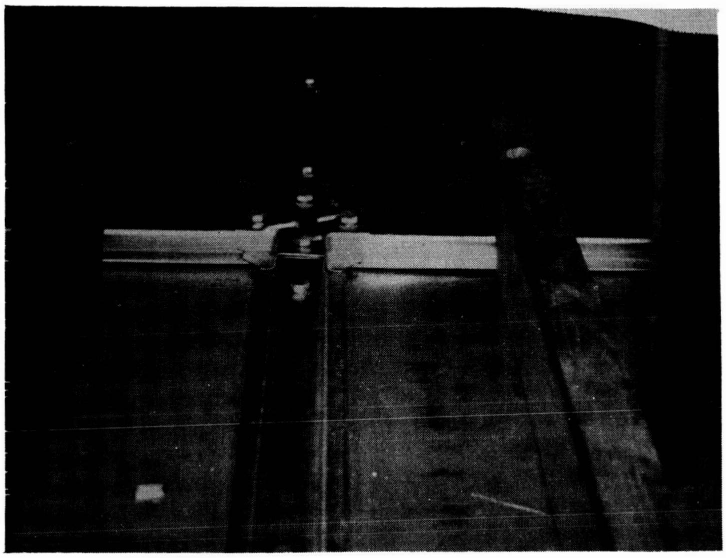


FIGURE 7 SHIELDED ENCLOSURE FLOOR JOINT

B. Development of Directional Probe at VHF

Some experiments using a directional coupler have shown that the signals (third harmonic or intermodulation product) generated in a diode or a junction flow out of the nonlinear element. Consequently, if a nonlinearly generated signal is measured in a particular structure, a braided cable for instance, and its direction of flow determined, then it is possible to determine in which direction the diode is located. Experiments on antennas can also be carried out to determine whether the nonlinear signal is going in or out of the antenna, thus permitting the linearity of the radiating system to be assessed. The design of the directional probe is based on the principle of the directional coupler.

A directional coupler is a device for individually sampling the RF incident and reflected wave in a transmission line. Assuming that a signal generated in a junction flows out of the nonlinearity as shown in Figure 8, then the directional coupler should indicate an incident wave flowing away from the nonlinearity on each side. By knowing which way the current is flowing one can find where the junction is. By going into a little more sophistication, one can sample both forward and backward waves at the same time, and feed the signals through an electronic switch so that the receiver reads the sampled signals one at a time. The receiver output goes again through an electronic switch which is synchronized with the first one, and the output of that switch goes to a differential amplifier which feeds a center reading meter. The meter reads zero when both signals are zero or equal, positive if one signal is larger than the other, negative if the reverse condition exists. Figure 9 is a block diagram of the system.

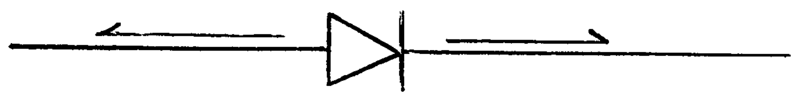


FIGURE 8 INCIDENT WAVE FROM NONLINEARITY

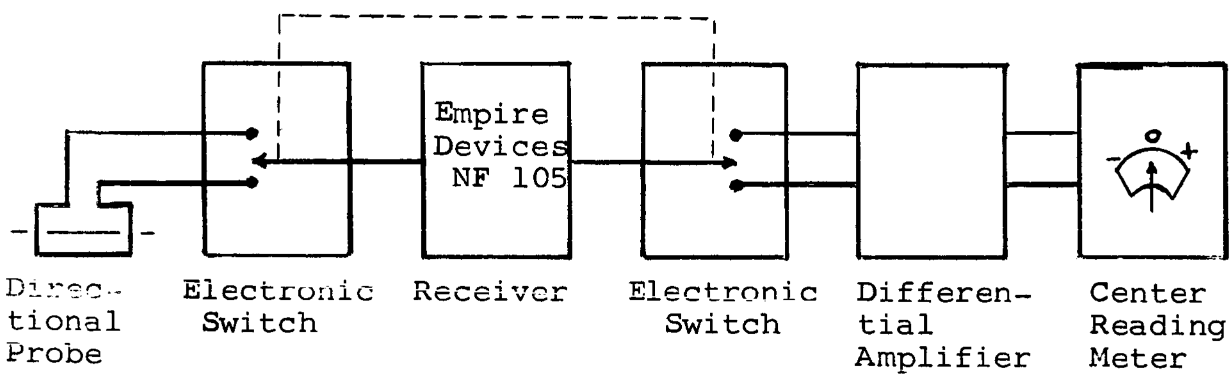


FIGURE 9 MEASUREMENT SYSTEM USED WITH DIRECTIONAL PROBE

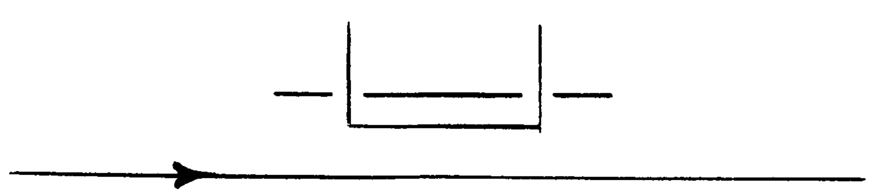


FIGURE 10 PROBE COUPLED TO CURRENT CARRYING CONDUCTOR

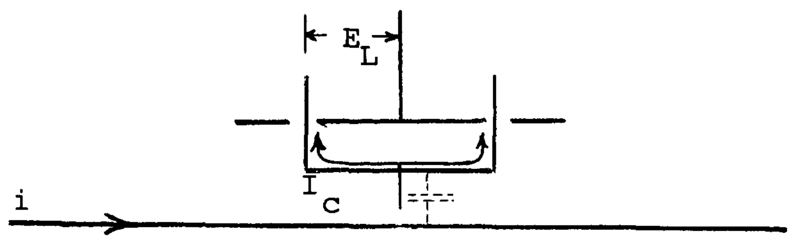


FIGURE 11-A

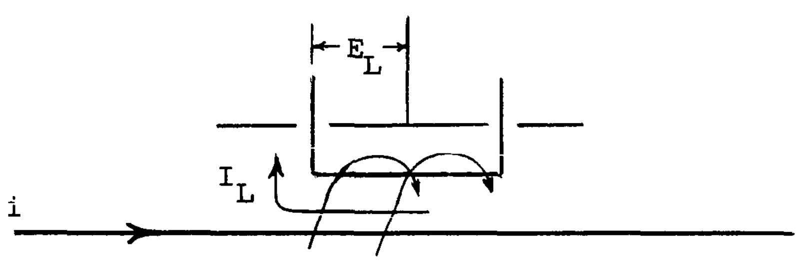


FIGURE 11-B

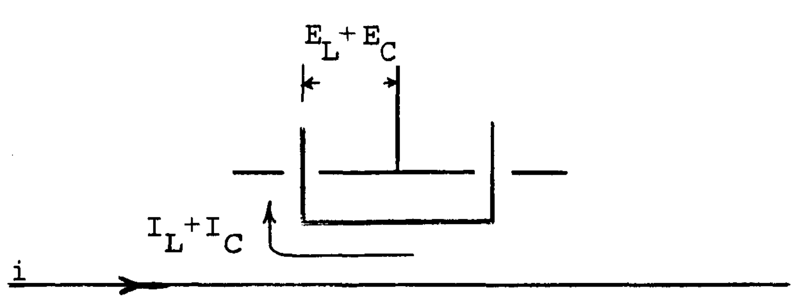


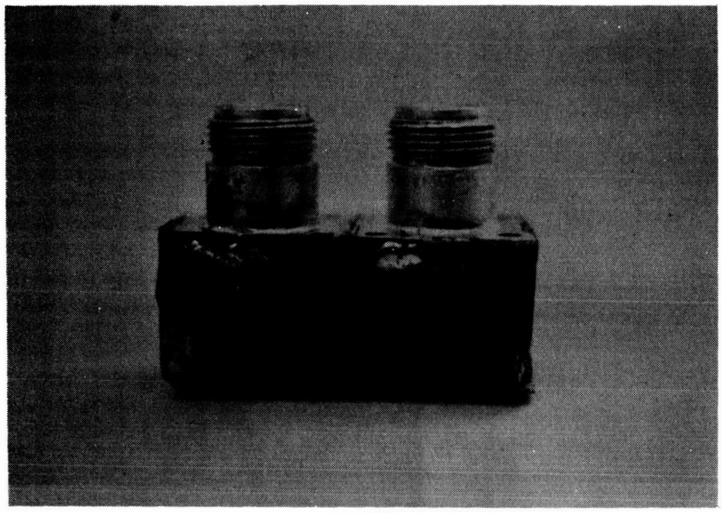
FIGURE 11-C

FIGURE 11 CURRENTS INDUCED INTO PROBE

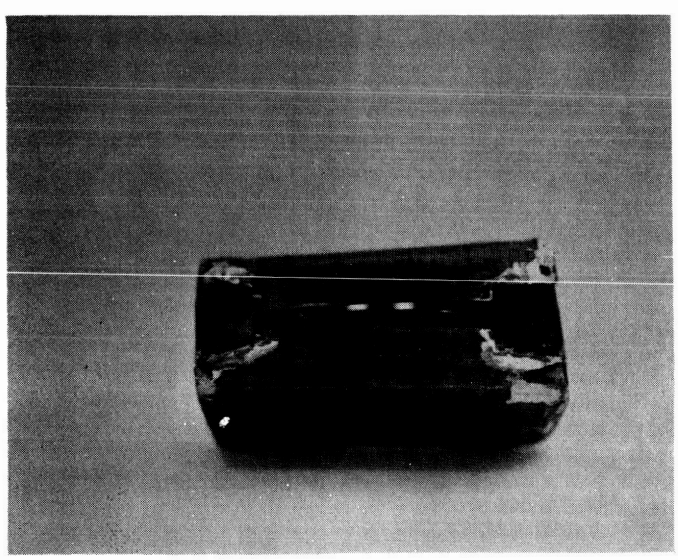
The directional probe is a loop-type directional coupler. The probe is coupled both capacitively and inductively to a line which carries a nonlinear current as shown in Figure 10. For a wave travelling to the right, the capacitance of the probe to the line will result in a current flowing in the probe as shown in Figure 11a. For the same wave, the inductive coupling of the probe will induce a current flow in the probe as shown in Figure 11b. In this case the capacitive and inductively coupled currents will add at the LHS output of the probe and will subtract at the RHS output as shown in Figure 11c. Normally, the inductive and capacitive coupling are made equal for better front-to-back ratio. This can be accomplished by proportioning the loop or coupling close to the wire that is to be sampled. This problem is relatively simple in the normal situation where the directional coupler is used in a transmission line of fixed characteristic impedance, but for the present application as a current probe on open wire it becomes a difficult proposition.

No provision was made for varying either the inductive coupling or the capacitive coupling in the first model of the probe which was made. Figure 12 shows two views of this probe. Tests of this unit revealed that the probe did not have a sufficient front-to-back ratio, i.e., some response to the total standing wave was being obtained.

In an attempt to alleviate the problems encountered with the first probe, a modified version was fabricated.

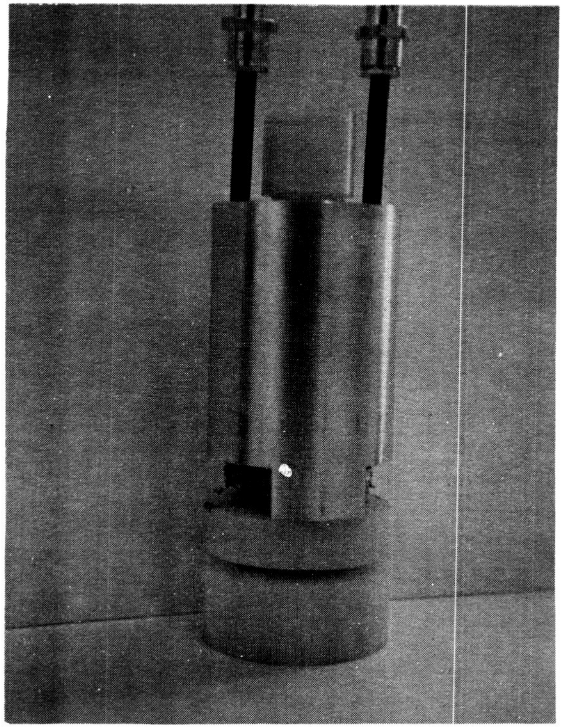


a. Side View of Probe

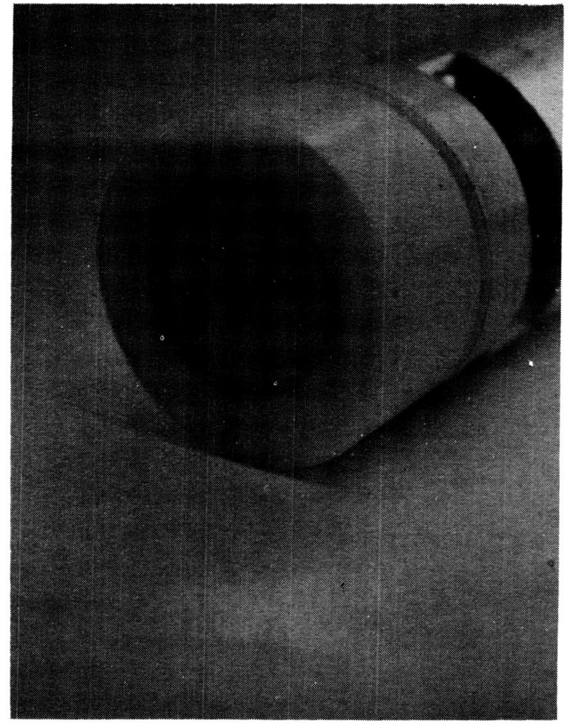


b. Bottom View of Probe

FIGURE 12 ORIGINAL DIRECTIONAL PROBE



a. Side View



b. Bottom View

FIGURE 13 MODIFIED DIRECTIONAL PROBE

The modified probe is shown in Figure 13. The modified version is an adjustable probe with a directional type of pickup loop. The probe has a shorted loop whose plane may be rotated relative to the plane of the pickup loop, thereby permitting adjustment of the mutual inductance between the pickup loop and the surface being tested. The amount of capacitive coupling with the surface may also be varied by adjusting the distance from the end of the pickup loop to the surface. In general, there is an optimum value of the ratio of magnetic to capacitive coupling for which the probe will yield maximum directivity without responding to the standing waves on the line. It is possible to locate junctions by looking for a change in the direction of the nonlinearly generated third harmonic incident wave, even when the magnitude of the directtivity fluctuates due to the standing waves, but this becomes very difficult when the fluctuations are large. For this reason, the probe was made adjustable. To simplify the experimental location of nonlinearities, the difference (rather than the ratio) in the current amplitudes in the two leads of the probe was taken to determine the direction of the incident wave.

The probe was tested on straight wire lines containing nonlinearities formed by parallel front-to-back diodes inserted in the lines. A motor was used to move the probe along the line, which was irradiated by a fundamental 223 Mc signal. The probe was connected to a receiver tuned to the third harmonic

(700 Mc), and a signal proportional to the difference in the amplitudes of the currents in the two probe leads was fed from a differential amplifier to a Sandborn recorder. A reference marker was put on the recorder graph as the probe crossed the nonlinearity.

Figure 14 shows a picture of the test setup for moving the probe uniformly along the line containing the nonlinearity.

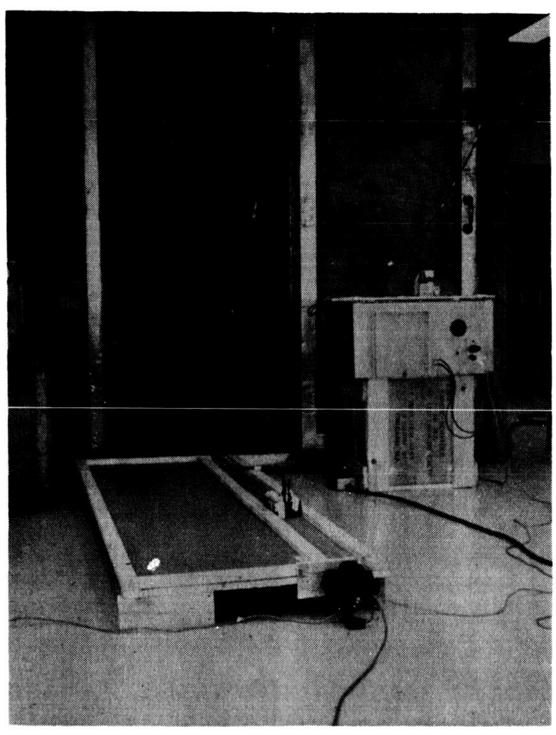


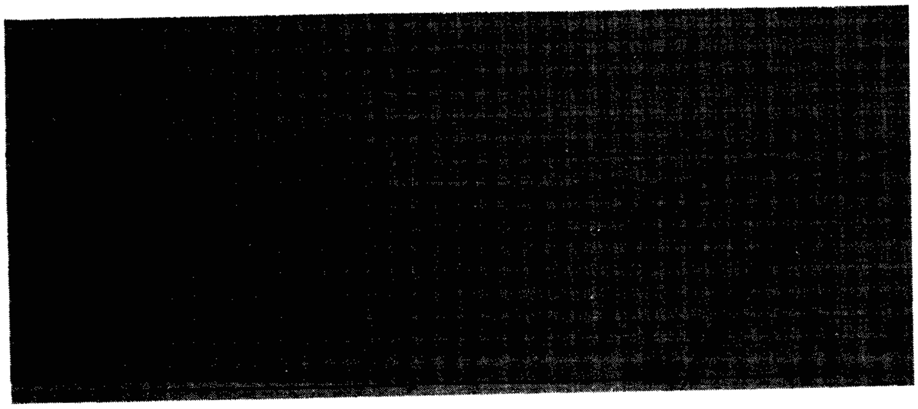
FIGURE 14 TEST SET UP FOR DIRECTIONAL PROBE EXPERIMENTS

The line in which the nonlinearity was placed was located beneath the cardboard track over which the probe was drawn. Figure 15 shows some typical recordings of the system output as a function of distance moved along the track. It can be seen that the direction of the current induced in the probe reversed as the probe crossed over the nonlinearity.

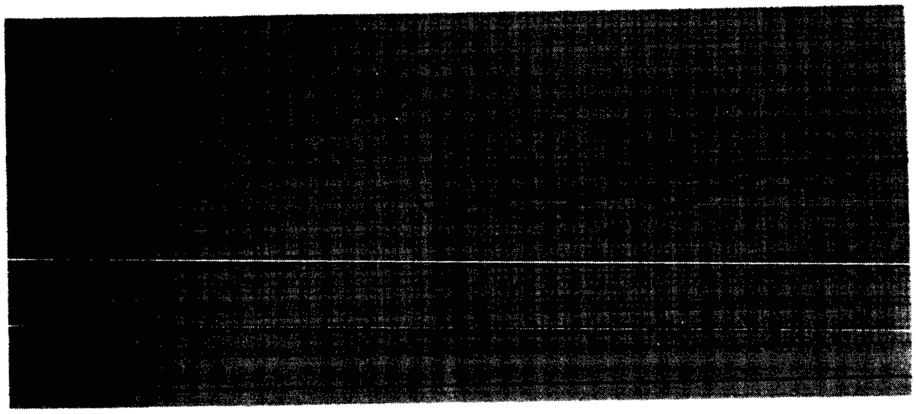
The first line tested was a thin wire line which gave poor results. The standing wave response was large and could not be reduced by any adjustment of the probe. Next, the thin wires were replaced by one-inch diameter copper pipes. The probe worked much better on this line, and the response to standing waves could be effectively minimized by proper adjustment of the probe. On this line the relative response to the standing waves of the third harmonic generated on the line was found to depend on the strength of the fundamental field and the orientation of the pipe in this field.

As can be seen from the graphs shown in Figure 15, the severity of the standing waves of the third harmonic received by the probe increased as the power transmitted increased. At high power levels the standing wave response was so great that location of a junction by observation of the pointer deflection was very difficult.

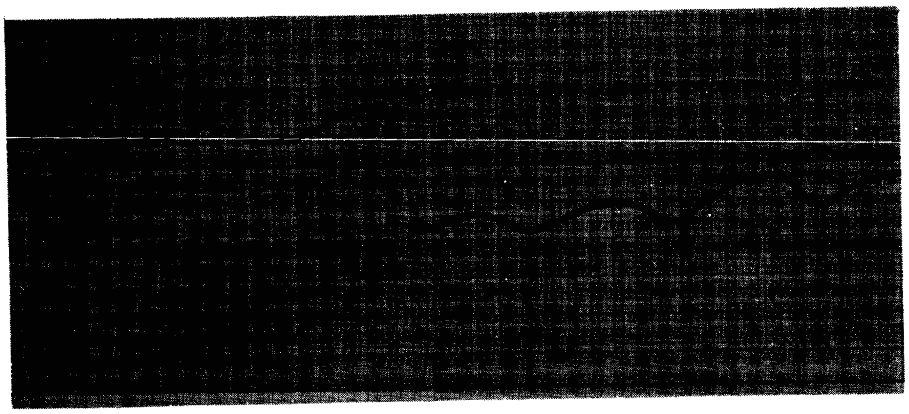
A possible explanation for this behavior is the fact that the dynamic junction impedance for the diode at any frequency depends on the level of the voltage across the junction. The standing wave ratio will depend, in part, on



a. -10 dbm Input to Power Amplifier



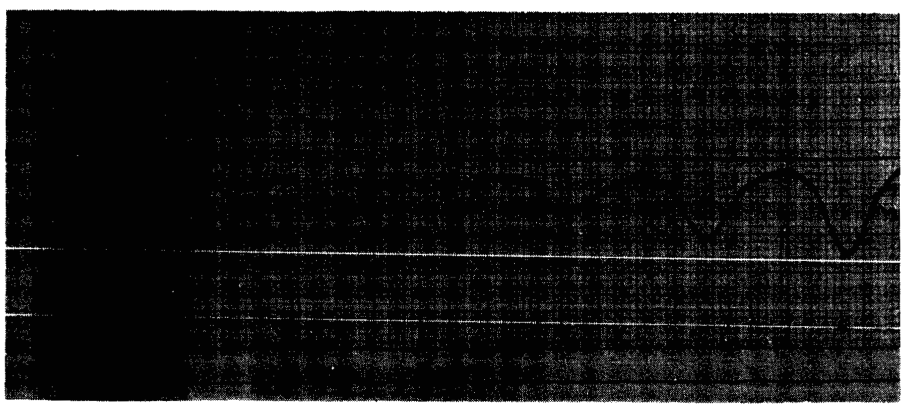
b. -3 dbm Input to Power Amplifier



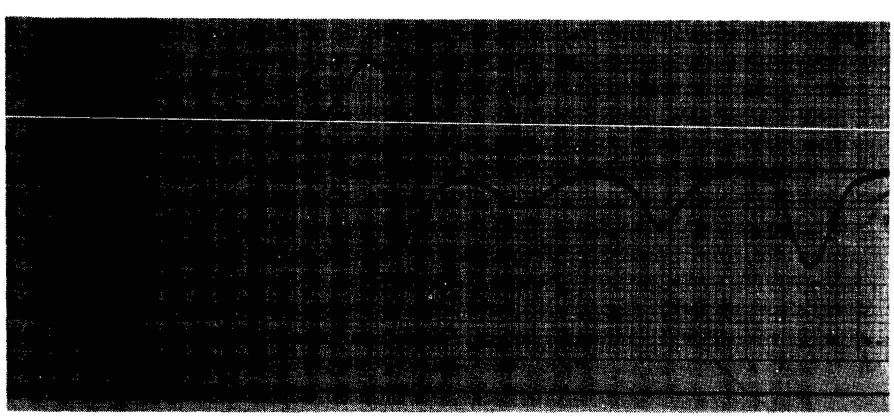
c. -6 dbm Input to Power Amplifier

FIGURE 15 DIRECTIONAL PROBE OUTPUT AS A FUNCTION OF DISTANCE MOVED ALONG A LINE CONTAINING A NONLINEARITY FOR VARIOUS VALUES OF RADIATED POWER

d. -4 dbm Input to Power Amplifier



e. 0 dbm Input to Power Amplifier



f. +4 dbm Input to Power Amplifier

FIGURE 15 Continued

the impedance at the junction, particularly since the end of the line is an open circuit and highly reflective.

The effect of frequency variations on the line was not investigated. If standing waves interfere with probe measurements on a given line, a slight change in frequency might reduce the effect enough to make the junction locating technique feasible.

It is evident that more experiments are necessary to improve the probe and assess its capabilities. For instance, the probe should be tested on lines containing more than one nonlinearity and on several lines in close proximity (each containing nonlinearities). Also, metal-oxide-metal nonlinearities and surfaces of a more general shape should be tested.

The motor driven mechanism which has been described is useful for adjusting the probe; however, a practical assessment of the probe can only be obtained by hand-holding the probe as in a normal search. Due to time limitations, efforts were diverted from the continued development of the probe to permit pursuit of the more general location schemes, which are discussed in the following section.

C. Investigation of Techniques to Locate General Nonlinear Areas

An investigation into the use of various antenna and signal processing schemes for the purpose of locating environment junction nonlinearities was made. The term "junction location" as it is applied here differs from that associated with the local probe techniques discussed previously in that, here, we are not concerned with locating the specific point of nonlinearity but in determining an approximate area from which nonlinear radiations occur and which should be investigated further by the local probe techniques. In effect, what was sought in the investigations to be described was a method for eliminating gross areas which do not contain nonlinearities and, thus, do not necessitate local probing.

The study of several omnidirectional radio range systems indicated very little applicability of the techniques used in these systems. While the use of omnidirectional antennas for junction location in the VHF-UHF band is very appealing, the nonlinearity bearing or direction information which would be generated in adaptations of these systems is due to phase comparisons. Such phase comparisons are ambiguous when a multiplicity of arbitrarily-located sources are present, which was the case at hand. It is apparent that an omnidirectional technique for locating environment nonlinearities cannot generate the direction or bearing information as phase difference but must generate the information in some other form; for example, as frequency differences.

In Appendix B a scheme utilizing a ramp modulated FM signal to measure the radial distance of a junction from the fundamental source is described. The technique is similar to that used in FM radio altimeters in that the distance information is contained in the frequency received; however, for the purpose at hand, an environment generated interference signal is sensed rather than the echo of the transmitted signal.

The FM scheme provides distance information rather than bearing indications and, thus, has only been considered theoretically. Implementation of the technique would involve some instrumentation problems; however, the concept appears feasible and should warrant further study at a later date if the information generated by this scheme would more rapidly permit the location of environmental nonlinearities.

1. Directional Location Techniques

Although VHF-UHF omnidirection location techniques would be desirable, the complexity of the problem may render such techniques ineffective. The [illegible]ive is to locate the approximate position of excited nonlinearities by use of directive antenna characteristics.

In using a "pencil beam" antenna for locating environmental nonlinearities, several factors must be considered. The antenna system to be used must be small enough to permit relative ease of manipulation. The beamwidth must be small enough to permit definite areas of nonlinearity to be pinpointed. The nonlinearity must be located in the far field of the antenna. Consideration of the above requirements will delineate suitable ranges of frequencies and types of equipment. However, the naturally-occuring nonlinearities must function at these frequencies in a manner similar to the way they function at the frequencies of concern. Specifically, the metal-to-oxide metal contact which is nonlinear at VHF must still be nonlinear at the frequency chosen for the directional location tests.

Tests were run to determine the operation of metal-oxide-metal junctions at third harmonic frequencies up to 6 Gc. The results revealed that for fundamental frequencies above 1 Gc, the efficiency of the nonlinear mechanism appears to fall off rapidly. The outcome of these tests, thus, determined to a large extent, the restrictions placed on the use of highly directive antennas for the purpose of locating specific areas of nonlinearity.

a. Preliminary Investigations

An investigation was performed to determine the feasibility of using directive antennas in the upper UHF and microwave regions to locate environment nonlinear junctions. Past experience has shown that both the transmitting and receiving antennas should be directive in order to minimize confusion due to reflections while attempting to locate nonlinearities.

Preliminary experiments were performed using a fundamental at 668.5 Mc and receiving the third harmonic at 2005.5 Mc. No directive antenna at the fundamental frequency was readily available; therefore, a cone antenna having an omnidirectional E-plane pattern was used. A horn was used to receive the third harmonic generated by a pair of front-to-back diodes in a relatively long dipole. Figure 16 shows the positions of the antennas for the test. The cross-hatched region shown indicates the general area within which the diode-dipole could be detected.

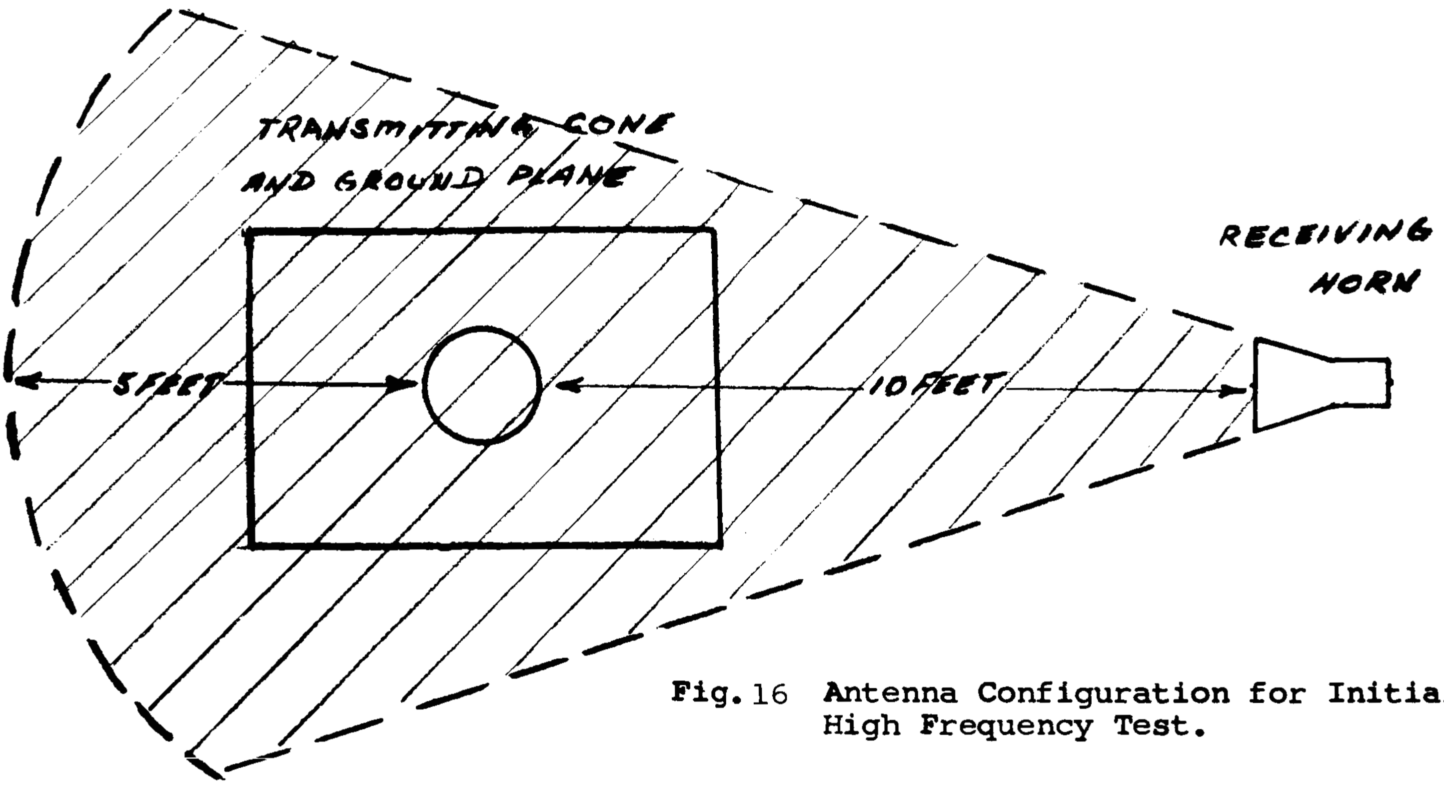


Fig. 16 Antenna Configuration for Initial High Frequency Test.

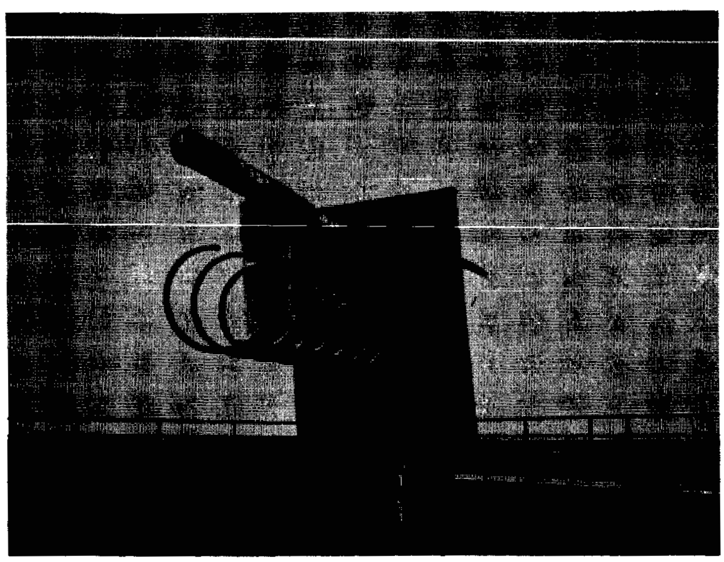


Fig. 17 First Model of Helical Antenna Pair for Junction Location.

Attempts to extend the above results to higher frequencies were not as satisfactory. These experiments were performed using a radiated fundamental at 2100 Mc. The fundamental power was six watts, which was radiated from an S-band horn. An X-band horn placed alongside the S band horn was used to receive the third harmonic at 6.3 Gc. A microwave diode in a dipole which was cut to a half wave at the fundamental could be detected at a distance of approximately six feet from the horns. However, a junction comprised of two steel screws in a nylon holder could not be detected at any distance. The junction was, however, driven nonlinearly by the modulated 2.1 Gc fundamental as was evidenced by the fact that the 1 Kc modulation signal could be received when the audio detector probe was connected across the junction. The test results indicate that the third harmonic generation and re-radiation at these frequencies are apparently so inefficient that prohibitive amounts of fundamental power would be required to permit junction location.

b. Helical Antenna Locator

The results of the foregoing experiments indicate that for the present, the frequency of operation for junction location devices should be restricted to the lower UHF band. Antennas which are to be useful as junction location devices should be as directive as possible and of such a size as to be portable and permit the necessary manuevering required. For the frequency range under consideration, it was decided that axial fire helical antennas, which can be made to occupy a relatively small volume with reasonable beam widths, appeared to be the most suitable antennas to use.

The use of helical beam antennas for locating environmental nonlinearities has the added advantage of circular polarization. This is an advantage since the polarization of the radiating element associated with any given environmental nonlinearity is unknown.

Two helical antennas mounted on a common ground plane were fabricated. The transmitting antenna was designed for a midband frequency of 440 Mc. The receiving antenna was designed for a midband frequency of 1320 Mc. The design frequencies chosen for the antennas were felt to be a compromise between antenna size and junction efficiency. Figure 17 is a picture of the prototype antenna pair which was constructed. A more rugged and maneuverable version has since been constructed and appears in Figure 18.

Tests indicate a transmitting antenna beam width of approximately 40° with 7 db gain over a horizontal dipole and 3 db gain over a vertical dipole. The receiving antenna has a beam width of approximately 23° and 12 db gain over a vertical monopole. The pattern for the pair used to excite a nonlinearity and receive the resultant third harmonic is approximately the same as the pattern for the receiving antenna alone. In an area free from detectable nonlinearities, the device could detect nonlinearities created by several touching armor sheath cables

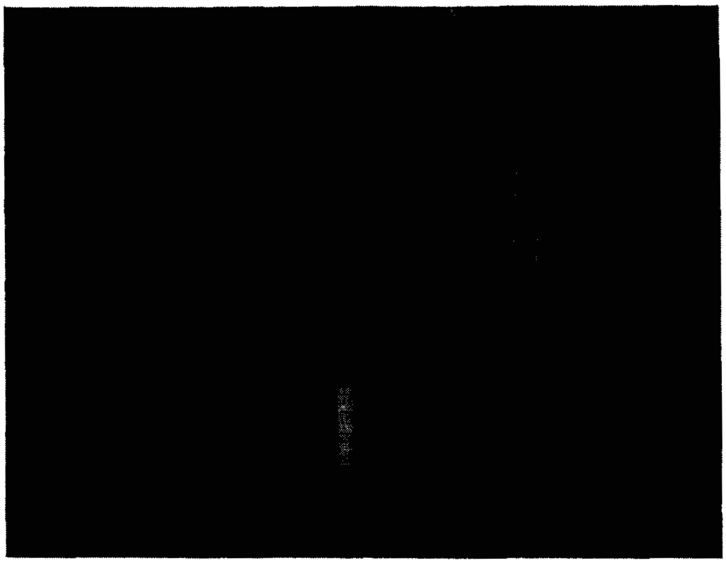


FIGURE 18 HELICAL LOCATOR USED IN LAUNCH STRUCTURE TESTS

at distances up to 25 feet. For these tests the fundamental power delivered to the antenna was in the order of five watts.

Figure 19 shows the pieces of armored cable used for the test, while Figure 20 shows the position of the antenna relative to the cables.

The antenna pattern measurements revealed that the two helices had side lobes, but they were not high enough to impair the use of the system as a locator. An effort was made to correct the situation by surrounding the antennas with absorbing material. However, the absorbing material was also found to be affecting the main lobe, decreasing the gain to a level where the

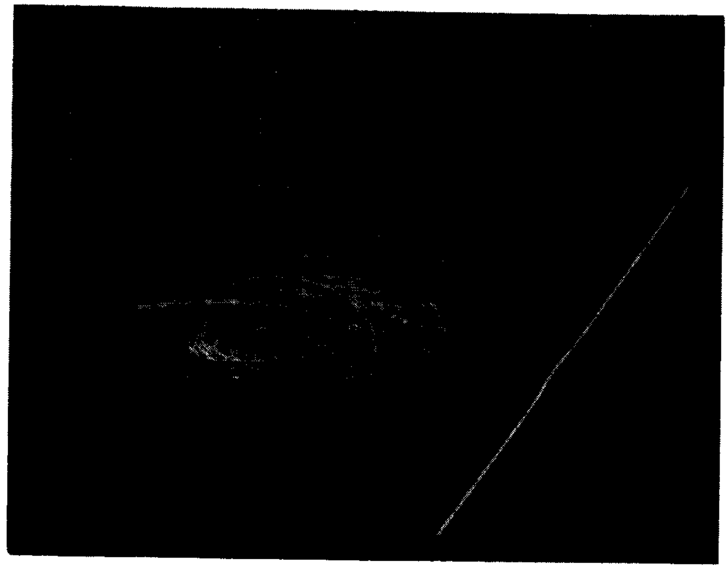


FIGURE 19 PIECES OF ARMORED CABLE TESTED

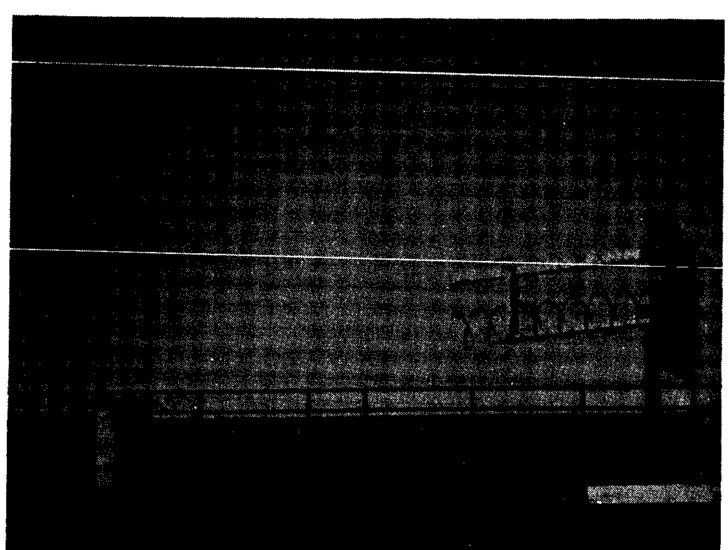


FIGURE 20 POSITION OF LOCATOR WITH RESPECT TO CABLES FOR TEST

range of the antenna was down to a few feet. Therefore, the absorbing material was removed and tests were continued with the original antenna in order to familiarize the test team with the most effective manner of using the device. The resolution of the locator was such that two junctions ten feet apart could be differentiated at a distance of twenty feet, and two junctions three feet apart could be differentiated at six feet. By moving the device closer to the nonlinearities and reducing the radiated power, the resolution was even better.

IV. FIELD TESTS ON SATURN LAUNCH STRUCTURES

A. First Field Test

The first field test was conducted at the outset of the program and was planned simply to gain some familiarity with the problem at hand and the types of structures involved at the launch complex. Techniques already known at the time, such as the audio technique, the local substitution technique, and the loop probe technique, were used in an effort to locate the major and most obvious nonlinearities.

A system consisting of two radiating antennas with appropriate power sources and a receiving antenna and receiver, was initially set up and tested in a shielded enclosure. It was found that a fairly high (approximately 50 db/noise) intermodulation level could be obtained within the enclosure when the two sources delivered two watts to the antennas. The two radiated signals were in the telemetry band.

Several contributing nonlinearities were found within the enclosure by various location techniques; however, after all nonlinearities which could be found were removed, intermodulation was still present (20-30 db/noise). It was, therefore, concluded that although the location techniques that were employed could locate many excited and contributing nonlinearities, all contributing environment nonlinearities could not be pinpointed by use of those techniques.

Investigations were conducted into the environment of SA-10 at the A-2 level within the clam-shell. Radiated tests with the system that had been used in the enclosure indicated environmental intermodulation. Several categories of structures were found to be contributors; however, no fixes of these sources were attempted. The test to verify that nonlinearities were present in the structure was set up as shown in Figure 21. The power level of each radiated signal was approximately four watts. The intermodulation level received was quite high.

To locate some of the contributors, the loop probe technique was used. Figure 22 depicts the functional arrangement of equipment used for this location experiment.

The signal at 225 Mc was induced by the probe into various structures. Whenever a nonlinearity was excited by both the 225 Mc signal and the 255 Mc radiated signal, a third order product at 735 Mc would be generated and subsequently sensed by the probe.

Many junctions were found in this manner. The most important contributors which were found are listed below.

a. The life lines around the vehicle - made of posts loosely dropped into slots and chains between posts.

b. An aluminum scaffolding.

c. A small portable stairway leaning against some pipes along side walls of the service structure.

d. Sliding panels on aluminum tracks.

e. Bundles of cables rubbing against each other.

The cables indicated in (e) were the umbilical cables connected to the vehicle.

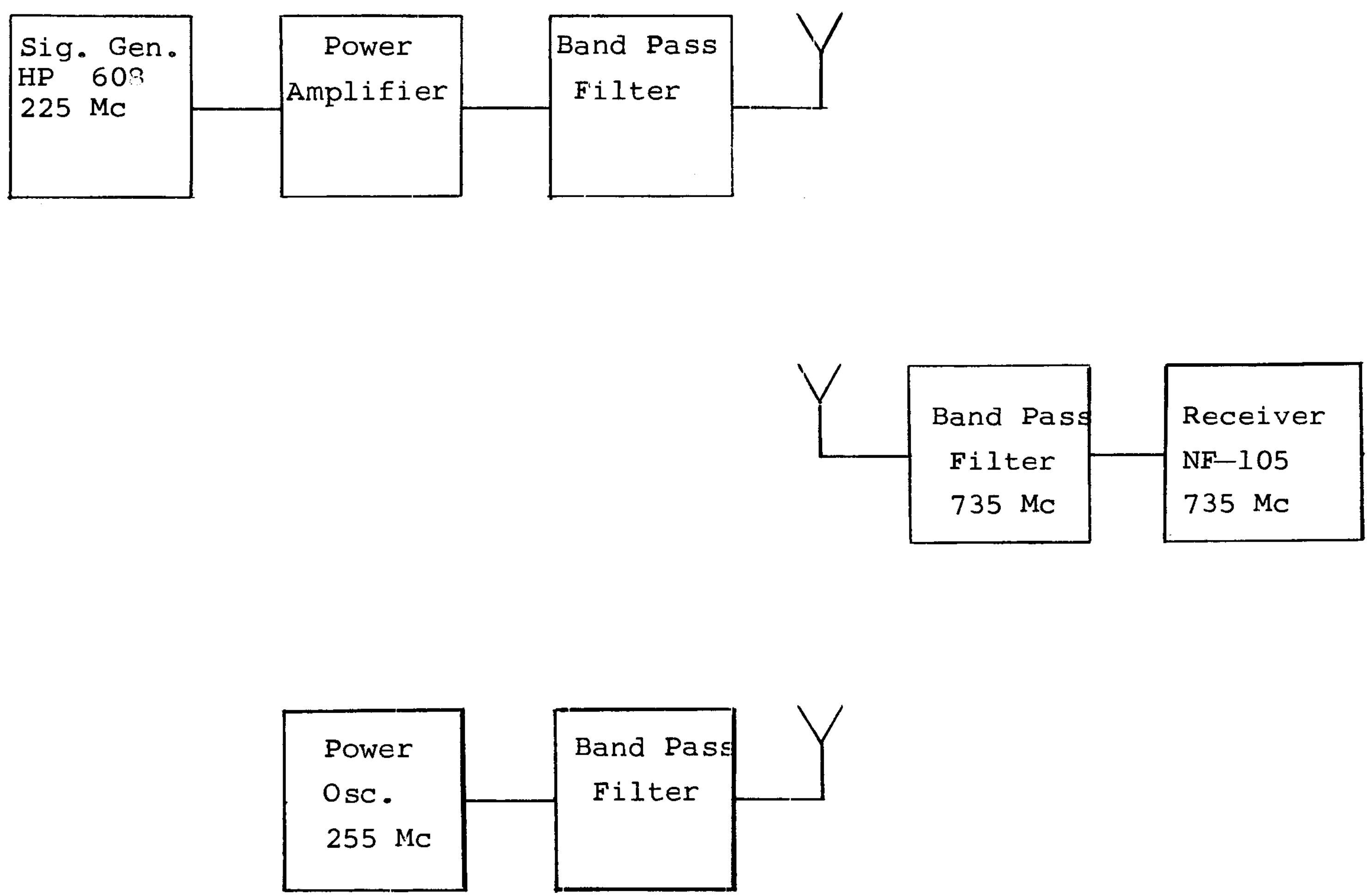


FIGURE 21 SYSTEM FOR FIRST TEST OF LAUNCH STRUCTURE

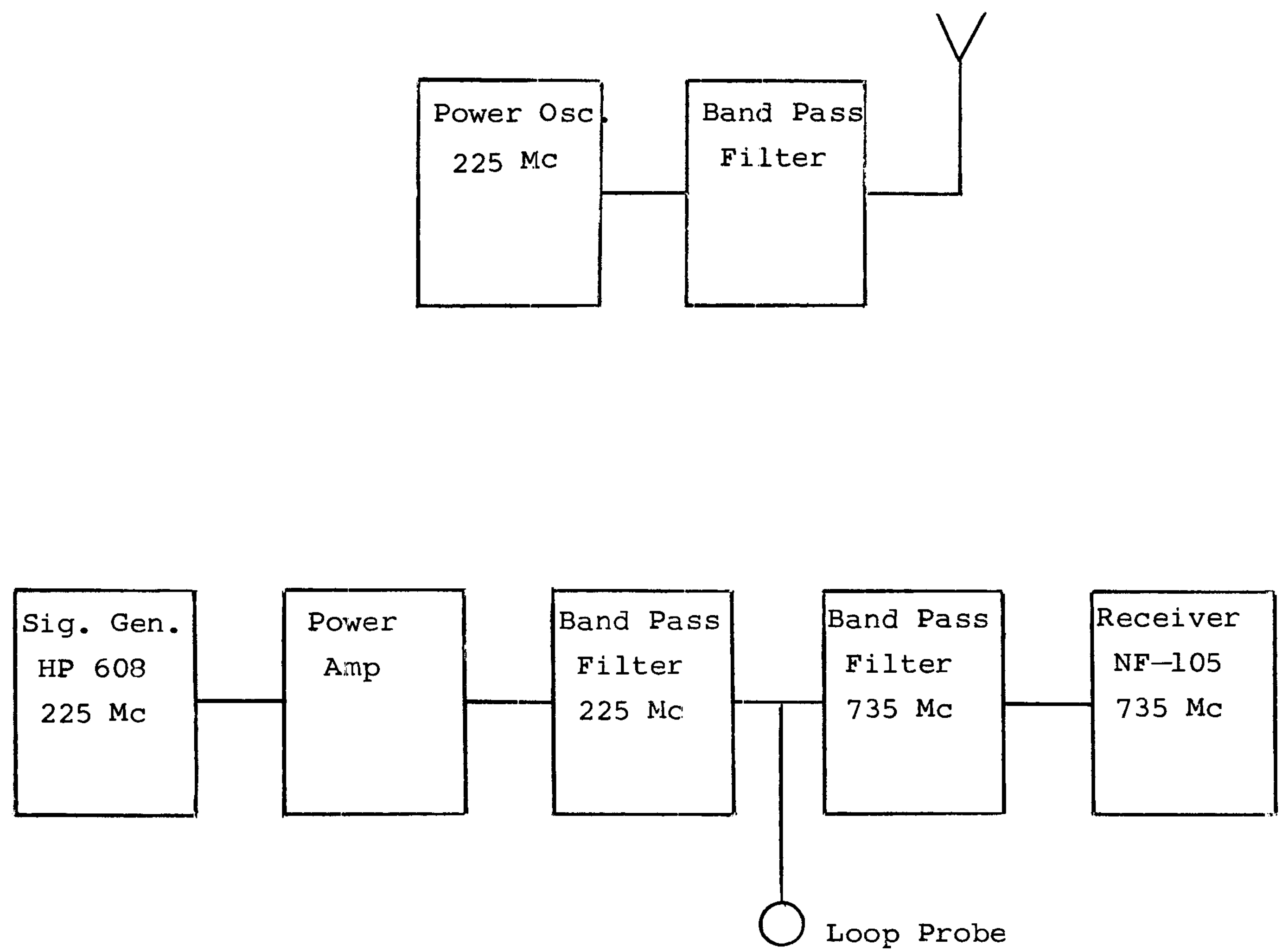


FIGURE 22 LOOP PROBE TECHNIQUE EQUIPMENT ARRANGEMENT

The audio probe technique was also used within the service structure. The radiated signal was at 225 Mc modulated by 1 Kc. Using this technique, two of the expansion joints on the floor could be detected as nonlinear. The sliding panels on aluminum tracks were again detected by the audio method, and the junction appeared to be at the point where the panel met the track.

The basic conclusion drawn from the first field test was that junctions exist in abundance within the service structure. Also, the location techniques used in the test, while permitting the isolation of many nonlinearities, were felt to be inadequate for the purpose of completely eliminating, or at least assessing, all points of nonlinear generation in such an environment.

The primary difficulty inherent in the techniques which were available for location use during the first test of the launch structures was the local search nature of these techniques. The use of such local probing techniques as the only method of locating nonlinearities requires considerable human judgment and experience. The size of the structure being investigated renders a square-inch by square-inch search of the environment prohibitive. Consequently, potential areas of nonlinear occurrence must be determined by visual inspection. These chosen areas can then be investigated in detail using the local probe techniques.

There are two obvious limitations to the above approach. The first is that areas of actual nonlinearity are not always apparent by visual inspection. The second is that without the realization that a nonlinearity does indeed exist in an area being probed, the possibility of missing a junction that is difficult to excite with the probe is always present.

The realization of the limitations on the use of local probe techniques alone for locating environmental nonlinearities prompted the investigation into the use of various omnidirectional and directional techniques for determining the location of contributing nonlinearities. These efforts, which have been described in a preceding section of this report, resulted in the development of the helical locator. The use of this device in conjunction with the local probe techniques circumvents the limitations inherent in the use of the local probe techniques by themselves. Namely, local probing is only necessary in areas that are determined to contain excited nonlinearities, thus obviating the visual assessment of the most critical areas; the certainty that a nonlinearity exists in a local area increases the likelihood of finding that particular source by the techniques available for local probing. The use of the above procedure for investigating typical launch structures is described in the following section.

B. Second Field Test

1. Umbilical Tower Tests

The purpose of the second series of tests at Cape Kennedy, which were conducted from August 31, 1965 through September 3, 1965, was to further assess location techniques which had been developed and to illustrate the occurrence of significant electrical nonlinearities in a physical environment in which construction practices are not tailored to preclude the incidence of such nonlinearities.

To locate general nonlinear areas the narrow beam helical antenna was used to transmit a relatively high power signal (two watts), and another helical antenna was used to receive the third harmonic signal generated by the nonlinearities located in the beam of the antennas.

To pinpoint mixing points, a small loop was used to irradiate local areas with a fundamental signal and to sense the re-radiated third harmonic from junctions excited by the fundamental signal. An audio probe was also used at times.

Initial tests were conducted on the third level of the umbilical tower at complex 37B. For this set of tests the only frequency available for use with the helical locator was 530 Mc. The equipment was installed on level 3 of the tower, which is flush with the concrete pad where the vehicle normally sits. Visual observations indicated that this particular level appeared to be relatively free of obvious points of potential nonlinearity.

A search pattern was established by placing the helical locator near the center of the level and radiating a signal of approximately two watts toward the periphery of the structure. A third harmonic signal was received when the antenna was pointing toward a set of four cable raceways running up along side the umbilical tower.

These galvanized steel raceways were made of two parts: a U-shaped section in which the cables were inserted and a cover that formed the fourth side of the raceway. The cover was attached to the U-shaped section with spring-loaded clips. By use of the helical locator, it was determined that a contribution to the total interference signal was being made by each of the four raceway covers. By applying pressure on the cover of the raceway, it was possible to eliminate the contribution from that cover. Thus, it appeared that the mixing point was the joints between the cover and the main body of the raceway. However, it was found later, that the clips holding the covers were the major contributors.

The search was continued in a clockwise manner and a very high level of third harmonic was received when the antenna was pointing at some small pipes running vertically next to the raceways. The mixing point was believed to be the joints between the pipes and the brackets holding them to the structure at various intervals. These joints were very rusty and could conceivably create partial contacts. These same pipes were connected to other horizontal pipes in such a way as to form loops which then became effective receiving and transmitting antennas. By applying pressure to these pipes, it was possible to either eliminate the signal completely or obtain a signal of the order of 30 db above the noise.

Next, the helical locator was directed toward the accordian door leading to the elevator. The door proved to be very nonlinear and the nature of the signal was very erratic. This was not surprising because of the numerous sliding and partial contacts in the door itself and between the door and the structure. Again, simply by touching the door slightly, the signal could be increased or decreased at will.

Finally, the only other place that gave any third harmonic response on the third level was where two six-inch water pipes were attached to the tower with steel brackets. The contact between the bracket and the pipe was rusty and the helical locator indicated that the nonlinear source was the pipe-bracket junction. Movement of the pipe, at least as much as possible, eliminated almost all of the signal, but the nonlinearity was re-established when the pressure on the pipes was released.

This completed the tests on the third level, having shown clearly that the helical locator was functioning properly.

Tests were then resumed on another portion of the same structure. A careful visual examination of the structure found that the eleventh level was a typical one and the results obtained there would probably reflect the situation at other levels. Figure 23 shows a sketch of that level.

The frequencies assigned for this group of tests were 450 Mc to be used in connection with the helical locator and 235 Mc to be used in the loop probe location technique. The

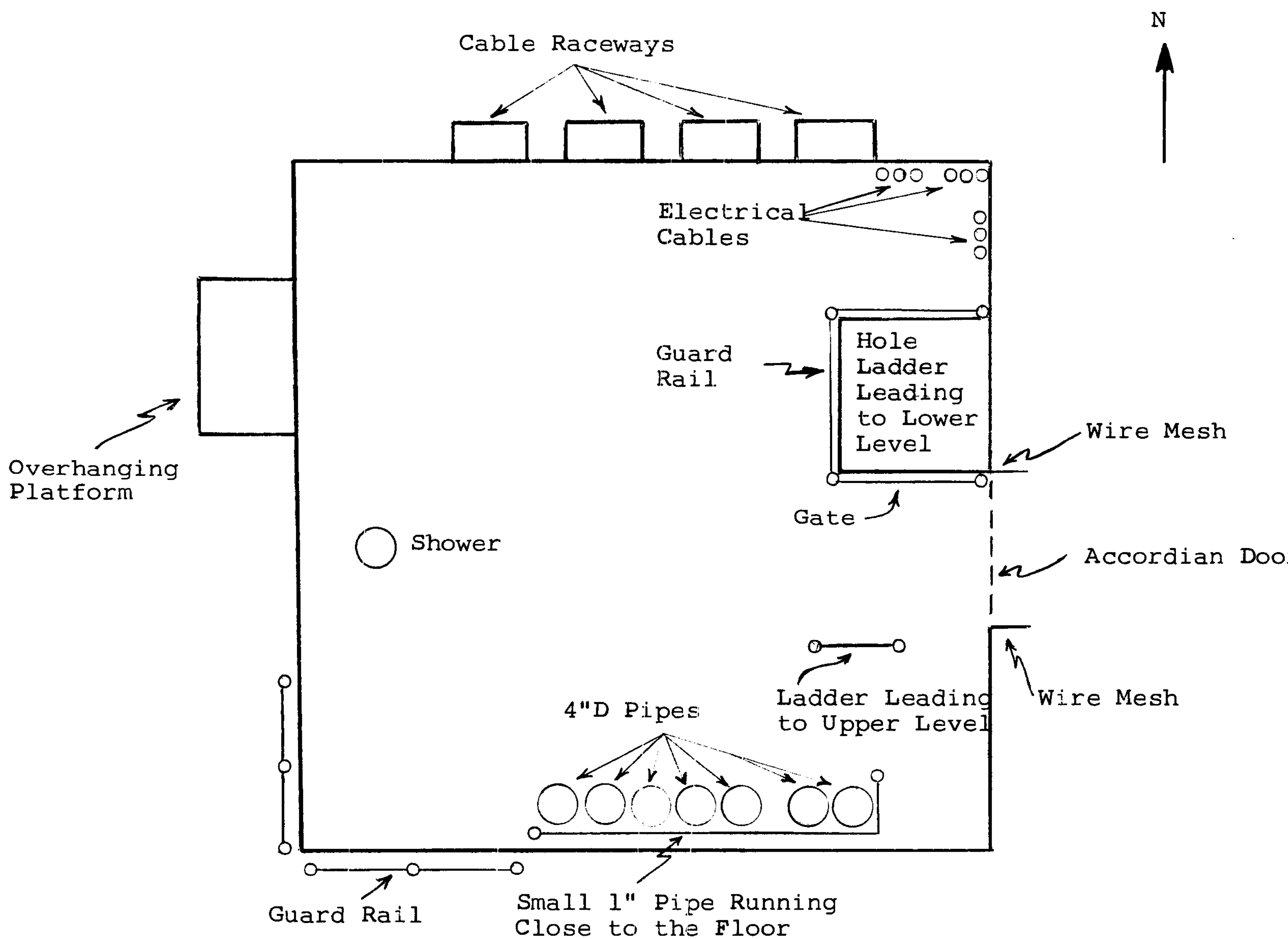


FIGURE 23 TOP VIEW OF UMBILICAL TOWER ELEVENTH PLATFORM - COMPLEX 37B

experiment was planned in the following way. First, using the directional antenna, all the areas containing nonlinear points would be systematically located and then, using the local probe technique, the exact mixing points would be pinpointed if possible.

The first nonlinearities located on the eleventh level were in a shower chain hanging down vertically. By moving the chain, the received third harmonic signal level could be changed considerably. The small loop technique later showed that the junctions were between the links.

When the antenna was directed toward the corner of the tower, at the point where the platform was attached to the structure, a small signal was received. The only item which appeared to be potentially nonlinear by visual observation in that general area was a removable guard rail that was slid into holes. However, moving the guard rail did not affect the signal. The small loop probe could not detect any junction either. We were then led to believe that either the structure could not be excited properly with the loop probe or that the helical locator was responding to reflections. It was found previously that particularly large structures are difficult to excite with the small probe, and that the orientation of the probe has to be just right in order to [illegible] the proper currents in the structure.

The search for junctions was continued by pointing the helical locator at the cable raceways of the type that were found to be nonlinear at the third level. They appeared to be even worse than the ones on the third level. There were four raceways, but it appeared that not all of them were contributors to the received interference. By decreasing the power level and moving the helical locator closer to the raceways, it was possible to tell which one of the raceways was contributing the most. By applying pressure on the cover of that particular raceway, the signal could be completely eliminated. The small loop probe revealed that the major offenders in this case were the clips holding the covers on the main body of the raceway. The partial contacts between the covers and the main body were also contributing but not nearly as much as the clips.

Next to the cable raceways were a number of rubber-covered electrical cables going up along side the tower. These cables were attached to the structure at various points with special clips that were affixed to small U-shaped cross beams called unistruct, which supported the cables. The clip was inserted sideways into the U-shaped unistruct and rotated 1/4 of a turn to lock it in place. The contact between the clip and the unistruct was, therefore, only a pressure fit which might become nonlinear through exposure to the saline atmosphere. A slight movement of the cables affected the received signal immensely.

The small loop probe technique corroborated the fact that the mixing point was at the points between the clips and the unistruct. In that particular structure most clips were nonlinear. When the small loop probe test was run, it was found that the fundamental signal could be induced directly into the rubber-sheathed cable at about two feet from any junction point and a third harmonic signal still could be generated. This meant that the fundamental signal induced in the cable was coupling capacitively to the clip and then conductively to the unistruct to create the third harmonic signal which, in turn, was coupled capacitively to the cable back to the loop probe.

Again on this floor, the accordian door leading to the elevator was found to be very nonlinear. The door structure itself was a big bundle of junctions. The door structure was made of 15 vertical aluminum strips attached to each other by other cross strips, with the possibility of a bad junction at each point, plus four sliding contacts holding the door in place. Simply by moving the door slightly the levels would easily change from 0 to 40 db above the noise. Using the small loop probe, a significant number of junctions could be detected; and by touching the door slightly, a junction could be created just about everywhere that there was a contact of some sort. This door made a very good receiving and transmitting antenna, with all of its 15 bars in the vertical plane. The situation was similar at all levels.

It was next found that a strong third harmonic signal was received while the antenna was pointing toward a group of seven four-inch pipes running up the side of the tower. There were a group of two and a group of five pipes. When the antenna was pointing toward the group of five pipes, the signal received was very strong. The angle of the antenna led us to believe that the contributing junction could be between the pipes and the platform, since the pipes were going through holes in the platforms. The holes were not perfectly round but had an irregular shape, having been cut with a torch. Since the holes were not much larger than the pipes, a slight movement of the platform could cause a contact between the pipes and the platform, thus, generating an interference signal.

By using the small loop probe afterward to corroborate the findings, it was found that the signal was not generated between the pipes and the platform, but rather by a small one-inch pipe running behind the large ones and parallel to the floor. This small pipe was periodically attached to the platform with the type of clips described previously. It was found that in three out of four cases the joint between the pipe and the clip was nonlinear.

By using the small loop probe, it was possible to corroborate all the findings of the directional helical antenna, and also it was possible to find other junctions left undetected by the directional antenna. One reason for this is that it is possible to excite nonlinearities, by close coupling with the loop, which will not be excited by a radiated field due to the absence of an effective antenna associated with the nonlinearity. The points which were found to be nonlinear when excited with the loop probe but did not respond to excitation by the helical locator are described in the following paragraphs.

The wire mesh on both sides of the elevator door showed many nonlinear points. Many of the points between the interlaced wire were making partial contacts, thus, creating nonlinear junctions.

Further investigation of the removable guard rails showed that the chain attached to the pin which locked the guard rail in place was the main contributor from the guard rail.

The three hinges on the small gate which guarded the opening to the ladder leading to the next level appeared to be a good mixing point. They were not detected previously by the directional antenna because they were very close to the accordian door, and the signal from the door masked the signal coming from the hinges.

One of the aircraft warning lights was found to be nonlinear by use of the loop probe. The junction was between the top cover and the main body of the light. The cover was only slid over the body and partial contacts were created by the oxide formed on the surfaces. This particular junction would probably be of minor importance, since it is not located in a structure capable of re-radiating a signal efficiently.

Finally, on that level, there were only two visibly potential nonlinearities. These were two steel cables, one attached between the southeast and southwest corners of the tower, the other between the northeast and northwest corners. These cables were rapped around the corner beams and insulated from it. Figure 24 shows how they were attached and where the junctions were. These junctions showed very strong to the local probe but were too far away for the directive antenna to locate them.

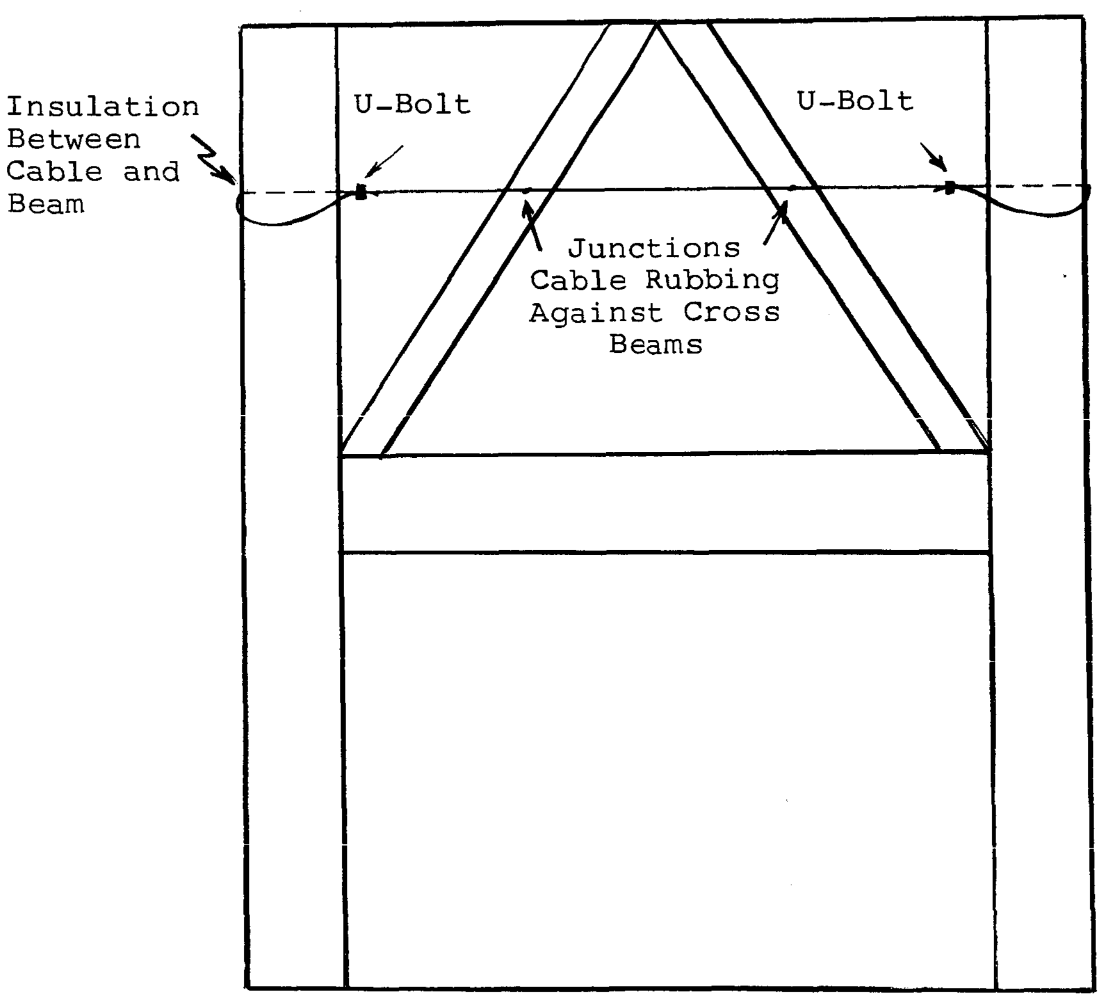


FIGURE 24 CABLE ARRANGEMENT ON UMBILICAL TOWER

These cables were making very good horizontally polarized antennas.

After almost all of the mixing points on that level were located, it appeared reasonable to investigate how these junctions would contribute to the interference environment of a particular antenna configuration at a particular frequency.

It was believed that in a particular situation, given a frequency and a set of antennas, a very small number of the junctions actually contribute to the received signal. This conclusion was based on the nature of the received interference signal which normally is continually varying over ranges of 6 to 10 db. Such a variation suggests that a relatively large percentage of the resultant interference signal was contributed to by a relatively small percent of the available nonlinearities. The changes noted in the received signal were caused by a nonlinearity changing state or shifting to a new characteristic. If the composite interference signal was being contributed to by many nonlinearities, the effect of a given nonlinearity changing state would be masked by the other contributors, i.e., the other nonlinearities would tend to average out the signal.

In an effort to corroborate the above hypothesis, a pair of vertical dipole antennas were mounted in the middle of the platform at the eleventh level. One dipole was set at 235 Mc to be used as a transmitting antenna, the other one set at 705 Mc to be used as a receiving antenna. With the power level set at eight watts, an environmentally generated third harmonic signal at 705 Mc was received. This signal was generated in either a few or all of the junctions already found on that level. Disturbing each junction in turn, it was found that the accordian door was a major contributor. Since the door was impossible to remove, both transmitting and receiving antennas were changed to horizontal polarization to reduce the effects of the door. Again a strong signal was received. Disturbing each of the junctions in turn, it was possible to attribute the great majority of the signal received to the two steel cables attached between the corners of the tower. There were a total of four junctions in the two cables, two per cable as is shown in Figure 24. One of those four turned out to be much worse than the others: the one close to the southwest corners of the tower. By isolating the steel cable from the cross beam, the remaining junctions appeared to be contributing an insignificant interference level. Consequently, the major contributor in that particular case had been found. This does not indicate that the cables were the only significant nonlinearities but that they were the worst offenders in that particular case of frequency, antenna location, and polarization. Therefore, if the significant nonlinearities within a structure are to be found, the search will have to be conducted by using signals radiating in all polarizations or by using a circularly polarized wave in order to excite all the junctions. The helical antenna used during this field test was, theoretically, circularly polarized.

However, antenna patterns showed that it was rather elliptically polarized and, improved performance of this device for location purposes could probably be effected if the polarization were improved.

2. Clam-Shell Tests

Tests were run within the clam-shell on complex 34, where a Saturn 1B vehicle was being erected. Because of the great activity on this pad, the choice of a site to conduct the test was governed by the inactivity at the level chosen, which was level A-3. The tower had just been recently put back in operation after a period of inactivity, and it appeared to be very clean to the point that it was doubtful that any junctions could be found.

The directional antenna was used initially to locate areas of nonlinearities. The first, and certainly the worst, offenders were the removable guard rails encircling the vehicle. The junction was the partial contact between the legs of the guard rail and the receptacle into which they were dropped. Most of those joints were found to be nonlinear and capable of generating significant interference. It is suggested that immediate attention be given to eliminating these nonlinearities on levels subject to vehicular radiation. The substitution of fiberglass stantions with nylon life lines is a simple solution to this problem.

The bundle of cables coming from the umbilical tower were also investigated and found to be serious offenders. Some of the cables were covered with protective metallic braid, and their rubbing against each other created partial contacts, which, in turn, generated the undesired signal. It was found that it took a very small movement of the cables against each other to create very efficient mixing points. The breeze from the ocean was sufficient to disturb the cables enough to generate large third harmonic signals.

Two other similar braided cables, one carrying water and the other pressurized air, were found to be rubbing against each other and generating high third harmonic signals. These cables were present at all levels, since they were part of the fire extinguishing equipment, and they formed good antennas because they hung vertically.

Again in this structure, the small U-shaped beams called unistruct, which are normally used as brackets to support cables, were found to be nonlinear; the junctions being between the clip attached to the cable or the pipe and the unistruct. However, on pad 34 those points were not nearly as bad as they were in the umbilical tower of complex 37, mainly because the tower had just been cleaned and repainted.

The metallic panels surrounding the tower were also investigated. On the previous field test, similar panels were found to be loose and partial contacts between adjacent panels were acting as good mixing points. But on complex 34 the panels were very tight, and although some points could be detected where the partial contacts between two adjacent panels were creating nonlinear signals, they were not major offenders. It must be remembered, however, that the salty atmosphere of that region can quickly deteriorate such a structure, and unless the structure is constantly maintained, problems of junctions may arise quickly.

With the local probe, it was found that some of the hinges on the portion of the platform immediately surrounding the vehicles were nonlinear. The same was found in the previous field test on pad 37.

Finally, use of the local loop probe showed any type of chain to be nonlinear. Normally the junction between each link was nonlinear. A small chain will not always be a serious problem, but in a particular case a chain could cause significant interference.

In summary, the purpose of the field test was to demonstrate the capability of locating points of interference generated by nonlinearities within the service structures. Use of the helical locator to isolate small areas within which nonlinearities exist, and use of the local probes to pinpoint the nonlinearities within these areas enabled a significant number of nonlinearities to be found. The nonlinearities found in the two field tests were not "fixed", therefore, it was not possible to determine whether all sources capable of contributing interference to a vehicular system had been located. It is believed, however, that application of the location techniques and devices developed on the program will permit all significant sources of structure-generated interference to be located.

V. CONCLUSIONS AND RECOMMENDATIONS

1. Steel remains nonlinear to at least within the VHF band. However, due to the high current concentrations required to generate intermodulation products, it is believed that the interference contribution of steel at VHF-UHF frequencies is secondary to that of nonlinear contacts.

2. Nonlinear contacts between metallic surfaces are quite easily formed and excited at VHF and lower UHF frequencies. Interference due to such nonlinearities is potentially severe due to the efficiency with which such interference can be re-radiated for structural components of reasonable physical size.

3. Experiments indicate that the efficiency of contact nonlinearities decreases quite rapidily as a function of frequency in the upper UHF band. Harmonics of frequencies above 1 or 2 Gc are difficult to generate and receive. However, interference to sophisticated systems within this frequency range possessing high powered transmitters; sensitive receivers; and high gain antennas is not inconceivable. Also, intermodulation products falling within the VHF and lower UHF bands which are created by fundamental frequencies in the upper UHF band solely or in combination with lower frequency fundamentals could at times pose a significant problem.

4. Two primary techniques have been used to pinpoint a contributing nonlinear junction. The first is by use of an audio probe which is, in effect, a sensitive audio amplifier. When a modulated RF fundamental current flows through a nonlinear junction, the nonlinearity acts as a detector, producing an audio component proportional to the modulation. The audio potential developed across the nonlinearity is sensed by the audio probe, thereby giving an indication of the presence of the nonlinearity.

The second method used to pinpoint the location of a nonlinearity is by the use of a small loop probe. A driving signal in the VHF band is fed to the probe. When the probe is brought into the near proximity of a nonlinearity, the third harmonic of the driving signal is created and, in turn, sensed by the probe. This method has been found to be quite effective in locating nonlinearities when it is known that a nonlinearity exists within a given search area of limited size.

5. The use of the audio locator and the loop probe technique, while being very useful to pinpoint sources of nonlinearity, are not suited for a general search of a large area unless they are complemented by techniques which are capable of locating nonlinearities in a more coarse sense. Research on the program has permitted many of the requirements for an intermediate distance locator, which complements the function of the audio and loop probe, to be delineated.

6. Practical experience has shown that within a confined structure, such as the clam-shell, where many reflecting surfaces exist, it is quite difficult to determine the approximate location of a nonlinearity from a distance unless both directional transmitting and receiving systems are used.

7. Investigations disclosed that for a practical intermediate distance locator, a compromise is necessary between the use of quite high frequencies for which highly portable and directive antennas can be obtained, and the use of lower frequencies for which the nonlinearity efficiency is sufficient to insure a positive location scheme. The frequency range chosen for the fundamental signal in the intermediate distance location scheme was 300 to 500 Mc.

8. Nonlinearities which form in the environment only give rise to interference when they are associated with a physical structure which can be excited by the transmitted signal(s) and can, in turn, efficiently re-radiate the resultant nonlinear product signals. Since the effective polarization of such a physical structure is a random variable, a practical intermediate distance locator should be circularly polarized.

9. A circularly polarized, portable, intermediate distance locator, having a fundamental design frequency in the 300 to 500 Mc band was designed and fabricated. The device detects nonlinearities by the re-radiated third harmonic of the fundamental frequency. The locator consists of two axial mode helical antennas mounted on a common ground plane. The antennas can be rotated 360° and directed to almost any vertical angle. The antenna mount is on wheels to facilitate maneuvering within the service structure.

10. Use of the intermediate distance helical locator in conjunction with the audio detector and loop probe permitted many nonlinearities within a typical launch service structure to be pinpointed.

11. It is believed that the search procedure and devices which have been developed would enable all contributing environmental nonlinearities within pertinent areas of a service structure to be pinpointed; however, since no fixes were made during the service structure tests which have been conducted, complete assurance that all contributors can be found by these techniques is not possible at this time. If such assurance is to be had, a validation test is necessary. For such a validation test, all nonlinearities which can be found by the available techniques should be fixed. An actual vehicular system or reasonable simulation should be used

to assess the interference reduction. Such an approach would: 1) Preclude against nonlinearities which are not excitable by the search system, 2) Serve as a check on the relevancy of the nonlinear steel phenomenon, 3) Serve as an additional check on vehicular system linearity.

12. Although the helical locator functions well, it is believed that its reliability could be increased by further testing and possible modifications. Only rough pattern measurements have been made on the unit which was constructed. Also, it is known that both the transmitting and receiving antennas have a certain amount of elipticity. Further characterization of the overall pattern and improvement of the polarization would permit the device to be used more effectively in the field.

13. The results of the testing at Cape Kennedy have indicated broad categories of items or construction practices which consistently give rise to interference generation when subjected to strong radiated fields. A partial list of groups of items which, due to their nature, exhibit a high probability of contributing to the interference environment wherever they occur are: 1) Pipes, hoses, and cables which are covered by armored braid. These cables, which are normally run in a group or bundle, have a high probability of generating interference wherever they touch one another. 2) Brackets and clamps, such as unistruct which is used to affix pipes and cables to the main

structure,are likely to form a nonlinear contact with the pipe or cable that they are holding. 3) Cable raceway covers can contribute to the interference environment due to the contact with the raceway housing proper. The clips used to secure the cover to the raceway have also been found to be a consistent source of difficulty.
4) The removable guard rails which encircle the vehicle were the strongest sources of interference found in the service structure. The nonlinear junction is the partial contact between the legs of the guard rail and the receptical into which they are fitted.

14. The research program has permitted the identification of broad categories of construction techniques, as listed above, to be classified as undesirable from the standpoint of interference generation. However, these individual categories have not been investigated in sufficient detail to permit specification of acceptable construction modifications. It is suggested that such an investigation be performed, the results of which would specify construction modifications acceptable from both an interference standpoint and from the standpoint of not degrading the normal function of the device to which the modification is applied.

15. The establishment of blanket modifications to be made on broad categories of construction techniques as is suggested above will greatly help in the control of environment

generated interference; however, there will always be items which contribute to the interference environment and which do not fall into any of the known categories. These contributors will necessitate rectification on an individual basis. To assist in handling such cases, which may become evident during critical periods, such as during system countdown, it is suggested that additional research be conducted to devise methods for rapidly assessing the environment and determining these points of nonlinearity. Such techniques would desirably not require large amounts of equipment and conceivably could be developed to pinpoint only those nonlinearities which contribute to a particular interference frequency and which are excited by only certain vehicular systems.

Respectfully submitted,
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APPENDIX A

NONLINEAR JUNCTION LOCATOR

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NONLINEAR JUNCTION LOCATOR

PURPOSE

Nonlinear junctions in the physical environment of transmitter/receiver installations can cause generation of spurious interfering frequencies when transmission and reception occur simultaneously. These nonlinearities can occur when metallic junctions are rusted, oxide-coated, corroded, or loosely-touching.

Instrumentation has been developed in the past* for locating nonlinearities in low-impedance circuits such as in loops or in flat sheets of metal, grills, etc. Such instrumentation operates inefficiently when the nonlinearities are located in high-impedance circuits such as whip antennas or loosely-touching, oxide-coated surfaces.

The device to be described has been developed to detect such high-impedance nonlinearities.

METHOD OF OPERATION

The basic device is shown in Figure A-1 and consists of a tone modulated RF signal source directly feeding a simple diode detector, the diode detector being the junction suspected of nonlinearity.

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*Report No. ARF-5181-13 (Final Report), "Engineering Study for Electrical Hull Interaction", Contract No. N123-(953)30698A Subproject No. S296002, Task 7407, Appendix F.

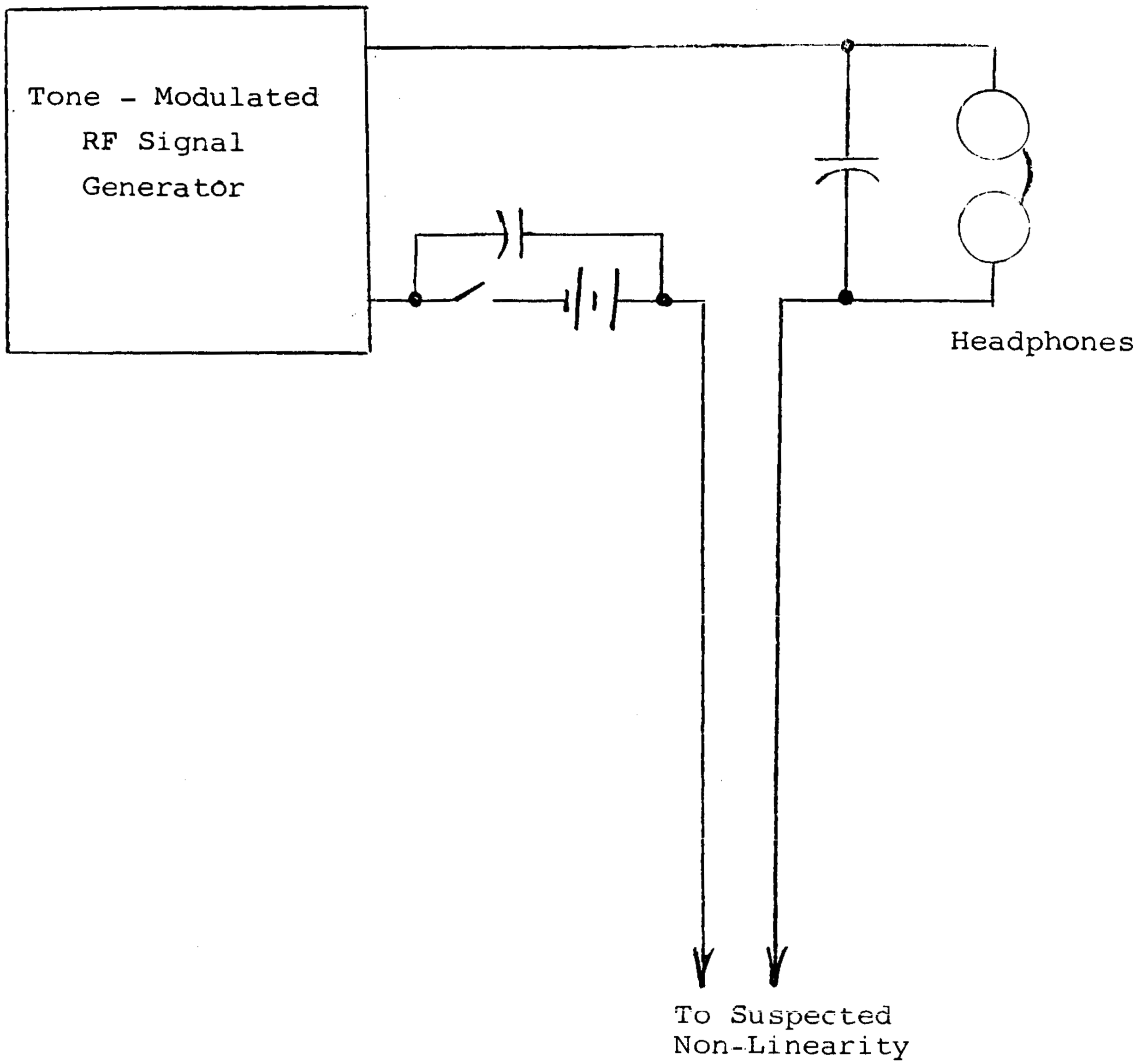


FIGURE A-1 - BASIC HIGH-IMPEDANCE JUNCTION LOCATOR

A nonlinear junction rectifies the RF signal and "detects" the audio tone which is heard in the headphones. No tone is heard if the junction is linear.

All environment nonlinearities and laboratory-fabricated junctions have been found to be symmetrical. Theoretically, a perfectly symmetrical nonlinearity cannot detect the audio modulation; however, most junctions do not possess perfect symmetry, but show some unbalance between the "forward" and "reverse" directions.

The addition of the DC bias causes the operating point of the nonlinearity to shift away from the zero reference so that rectification becomes more pronounced, especially in the case of nearly-perfect symmetrical junctions.

The basic circuit is not sensitive to frequency nor is frequency stability a problem. It is possible to use a low frequency so that the test leads could be made very long without having the device become critical. Under certain circumstances, these long leads could be "zeroed in" on a high-impedance nonlinearity existing between them. For specific applications, the RF frequency could be chosen so as to test suspected junctions at actual generated intermodulation frequencies.

Figure A-2 shows the schematic diagram of an audio detector which has been fabricated. For this version of the device, no internal RF source was supplied. A modulated RF signal is radiated within the environment being tested and

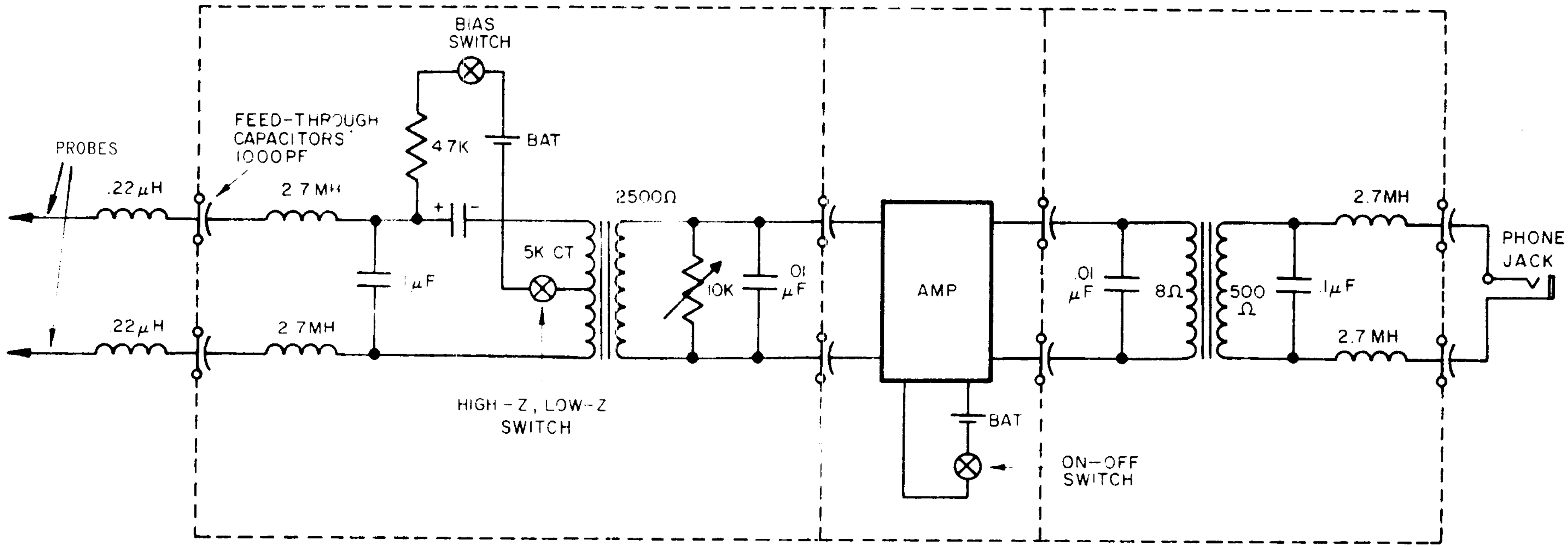


FIGURE A-2 EXPERIMENTAL HIGH-FREQUENCY JUNCTION LOCATOR the audio probe is used to locate nonlinearities which are being excited by the radiated field.

ADVANTAGES

1. This device can locate both symmetrical and nonsymmetrical nonlinearities in high-impedance locations in local communications environments.

2. It can be made light and portable.

3. It can be tailored to meet specific situations such as locating environment-generated intermodulation sources, using device frequencies identical to received spurious environment-generated intermodulation frequencies.

4. It can also be designed to use frequencies sufficiently low that long test leads could be used to "zero-in" on an environmental nonlinearity.

TEST TO DETERMINE SENSITIVITY OF AUDIO JUNCTION DETECTOR

The experiment was run using an Audio Signal generator @1000 cps (HP-205AG) feeding a Millivac Voltmeter. The audio detector was connected across the input to the voltmeter.

The sensitivity test was run as follows:

> For each of the signal generator output impedance positions, i.e., 50, 200, 600, or 5000 ohms, the output voltage was set at 1 volt. The audio detector was then connected across the output, and attenuation was then added in series at the output until the tone in the earphone became barely audible.

RESULTS

Sig. Gen. Output Imp.	Switch Pos. on Audio Detector	Attenuation Added	Sensitivity μ Volts
50	Low Z	100	10
	Hi Z	100.5	9.4
200	Low Z	102.5	7.5
	Hi Z	100.5	9.4
600	Low Z	105.5	5.3
	Hi Z	101	9.0
5000	Low Z	112	2.5
	Hi Z	104.5	6.0

Figure A-3 shows the experimental set up.

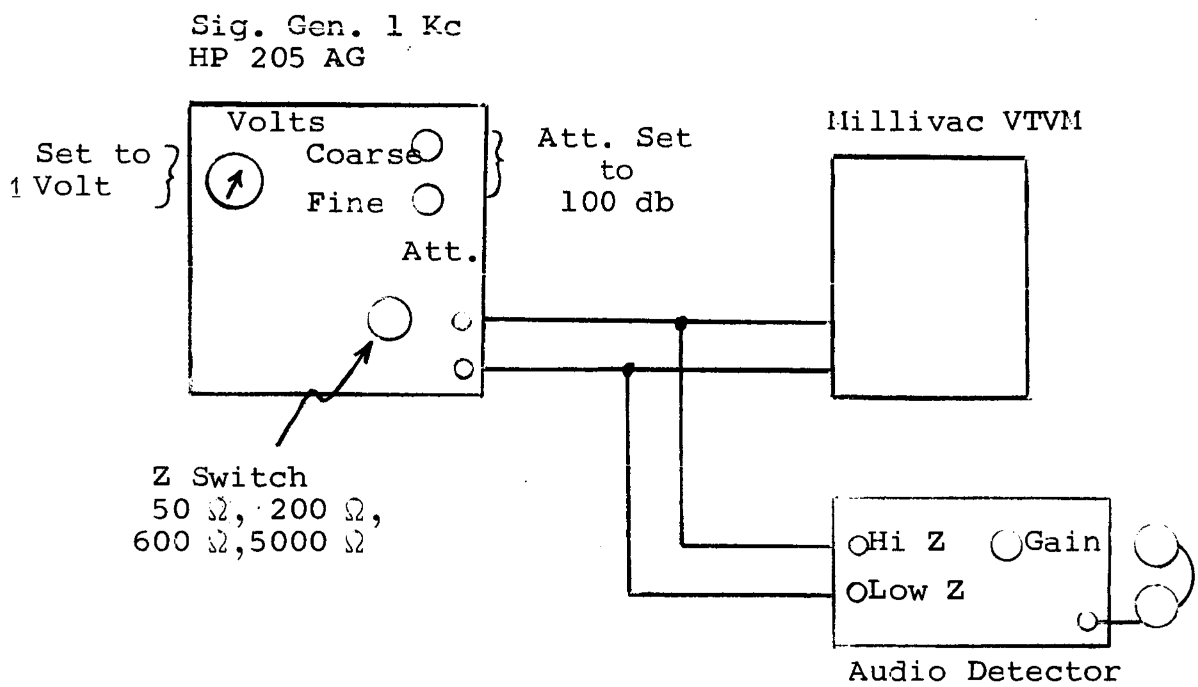


FIGURE A-3 EXPERIMENTAL SET UP

APPENDIX B

DISTANCE SEPARATION BY RAMP MODULATED FM

APPENDIX B

DISTANCE SEPARATION BY RAMP MODULATED FM

Consider the system shown in Figure B-1.

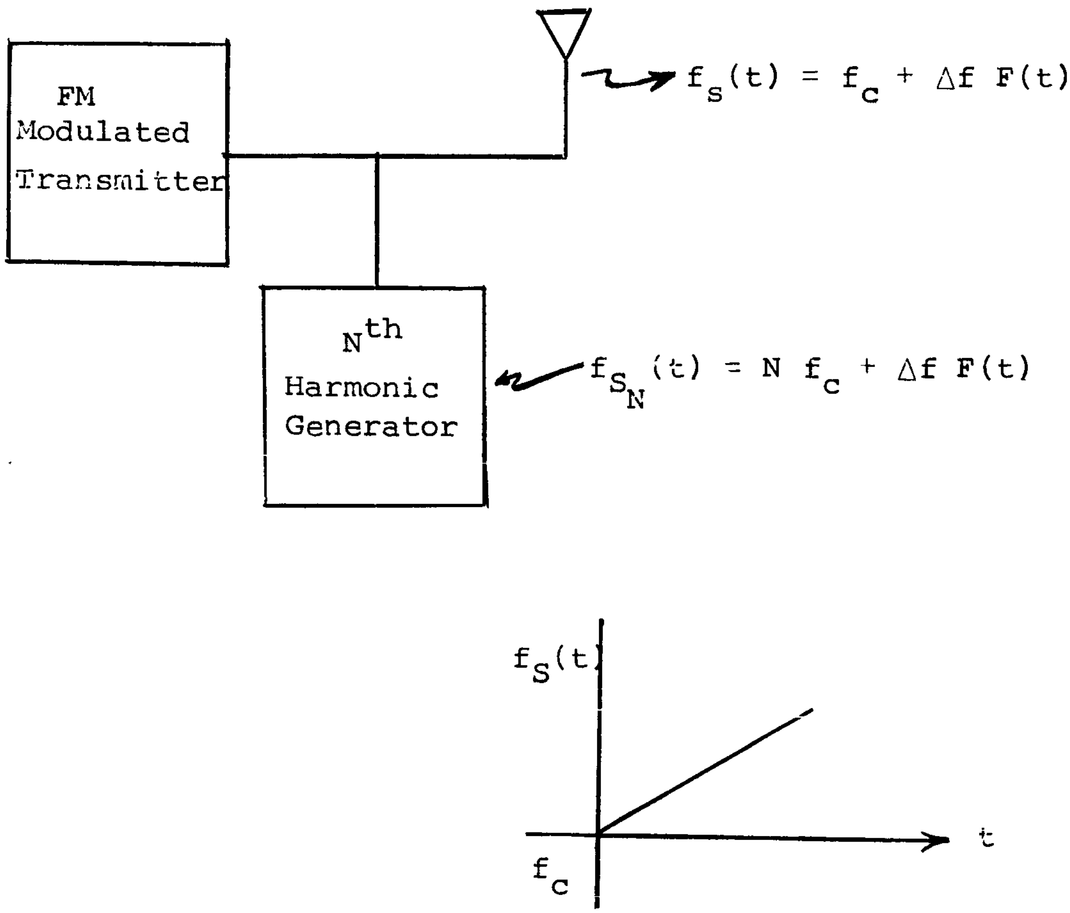


FIGURE B-1

Let the nonlinearities generating the Nth order harmonic be located t_1, t_2, ... t_m time distance away from the source. Also, let

$$S_N \cos \left\{ 2\pi N \left[f_c t + \Delta f \int_0^t F(t)\ dt \right] \right\}$$

be the Nth harmonic of the transmitted signal. Its instantaneous frequency is

$$N\left[f_c + \Delta f\, F(t)\right] = f_N(t).$$

The received signal from nonlinearity m is

$$R_m = A_m \cos\left\{2\pi N\left[f_c t + \Delta f \int_o^{t-2t_m} F(t)\, dt\right]\right\}$$

and its instantaneous frequency is

$$N\left[f_c + \Delta f\ F(t - 2t_m)\right] = f_{R_m}(t).$$

The total received signal R is, therefore

$$R = \sum_{m=1}^{M} R_m = \sum_{m=1}^{M} A_m \cos\left\{2\pi N\left[f_c t + \Delta f \int_o^{t-2t_m} F(t)\, dt\right]\right\}.$$

If the received signal is mixed with the Nth harmonic generated at the transmitter, each contribution will produce its own beat frequencies, f_{B+} and f_{B-}, with the local Nth harmonic. For the junction m,

$$f_{B+_m} = f_{S_N} + f_{R_m} = N\left[f_c + \Delta f\ F(t)\right] + N\left[f_c + \Delta f\ F(t - 2t_m)\right]$$

$$= 2Nf_c + N\Delta f\left[F(t) + F(t - 2t_m)\right],$$

$$f_{B-_m} = f_{S_N} - f_{R_m} = N\left[f_c + \Delta f\, F(t)\right] - N\left[f_c + \Delta f\, F(t - 2t_m)\right]$$

$$= Nf_c - Nf_c + N\Delta f\left[F(t) - F(t - 2t_m)\right]$$

$$= N\Delta f\left[F(t) - F(t - 2t_m)\right].$$

If F(t) is a linear function of time, the beat frequency will be proportional to the distance to the junction.

If, now, signal R is mixed with S, where

$$S = S_N \cos\left\{2\pi N\left[f_c t + \Delta f \int_o^t F(t)\, dt\right]\right\},$$

the signal B results:

$$B = K\, S_N \cos\left\{2\pi N\left[f_c t + \Delta f \int_o^t F(t) dt\right]\right\} \sum_{m=1}^{M} A_m \cos\left\{2\pi N\left[f_c t + \Delta f \int_o^{t-2t_m} F(t)\, dt\right]\right\}$$

$$= \sum_{m=1}^{M} KA_m S_N \cos\left\{2\pi N\left[f_c t + \Delta f \int_o^t F(t)\, dt\right]\right\} \cos\left\{2\pi N\left[f_c t + \Delta f \int_o^{t-2t_m} F(t)\, dt\right]\right\}$$

$$B = \frac{KS_N}{2} \sum_{m=1}^{M} A_m \left[\cos\left\{ 2\pi N \left[2f_c t + \Delta f \left(\int_0^t F(t)\, dt + \int_0^{t-2t_m} F(t)\, dt \right) \right] \right\} + \cos\left\{ 2\pi N \left[\Delta f \left(\int_0^t F(t)\, dt - \int_0^{t-2t_m} F(t)\, dt \right) \right] \right\} \right].$$

Passing this signal B through a low pass filter to eliminate the higher frequency components gives

$$B' = \frac{KS_N}{2} \sum_{m=1}^{M} A_m \cos\left\{ 2\pi N\, \Delta f \left[\int_0^t F(t)\, dt - \int_0^{t-2t_m} F(t)\, dt \right] \right\}$$

$$= \frac{KS_N}{2} \sum_{m=1}^{M} A_m \cos\left\{ 2\pi N\, \Delta f \int_{t-2t_m}^{t} F(t)\, dt \right\}.$$

The instantaneous frequency of the mth component is

$$f_{i_m} = N\Delta f \left[F(t) - F(t-2t_m) \right].$$

Example:

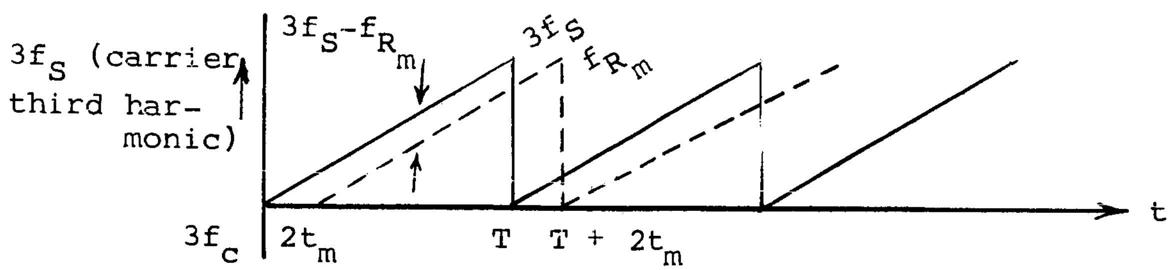
Assume a junction to be roughly 100' or 30 meters from the point where the fundamental signal is launched. Then, since

$$t = \frac{d}{v} = \frac{30 \text{ meters}}{3 \times 10^8 \text{ /sec}} = 0.1 \ \mu \text{ sec.},$$

$$\therefore t_m = 0.1 \ \mu\text{sec}$$

Let N = 3 (third harmonic)

Let T = 100μsec (10 Kc ramp modulation) as shown in the Figure.



T must be greater than $2t_m$.

Let Δf = 10 Mc.

Then,

$$f_{B-} = N\Delta f \left[F(t) - F(t-2t_m) \right].$$

But $F(t) = \frac{t}{T}$,

so

$$F(t - 2t_m) = \frac{t - 2t_m}{T},$$

$$\therefore \quad f_{B-} = \frac{N\Delta f}{T} \left[t - t - 2t_m \right]$$

$$f_{B-} = 2N\Delta f \left[\frac{t_m}{T} \right]$$

$$= 2 \times 3 \times 10 \text{ Mc } \frac{.1}{100} = 60 \text{ Kc}$$

$$f_{B-} = 60 \text{ Kc}.$$

Thus, for this example, a 60 Kc received signal would indicate a nonlinearity located at a distance of 30 meters from the source. Other nonlinear sources, located at different distances would produce different output frequencies. The deviation frequency and sweep frequency chosen for this example are not necessarily the best choices for an operating system; however, they illustrate the principle.

It is noted that this scheme generates information on the distance from the source to the nonlinearity, but gives no useful bearing information. Consequently, directional antennas or some additional scheme is necessary to obtain this information. The FM scheme was not pursued beyond the point presented here, since it was felt that work toward the development of techniques to obtain bearing information was a necessary prerequisite to this or any other distance measuring scheme.